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DIASTROPHISM AND THE FORMATIVE PROCESSES

XII. THE PHYSICAL PHASES OF THE PLANETARY NUCLEI DURING THEIR FORMATIVE STAGES

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In an article in the first number of this volume of the *Journal* a study of the relative densities of the moon, Mars, Venus, and the earth brought out the fact that the mean densities of these bodies not only rise in the order of their masses, but that the rate of increase itself rises with each unit-increase of mass.[1] This led to a study of the processes by which these bodies acquired their material, to see whether any part of the observed higher density could reasonably be assigned to greater proportions of inherently heavy material received during their formation. The conclusion was reached that larger proportions of *light* material entered into the formation of the large bodies than into the small bodies. The natural inference from this is that the higher mean densities now found in the larger bodies are due to some form of mass-effect that was sufficient to

[1] "The Order of Magnitude of the Shrinkage of the Earth deduced from Mars, Venus, and the Moon," *Jour. Geol.*, Vol. XXVIII (1920), pp. 1–17. Compare this with the theoretical deductions of Dr. A. C. Lunn, "Geophysical Theory under the Planetesimal Hypothesis, in the Tidal and Other Problems," *Carnegie Institution Publication No. 107* (1909), particularly pp. 188 and 201. Compare also the very suggestive paper of Dr. Wm. D. MacMillan "On Stellar Evolution," *Astrophys. Jour.*, Vol. XLVIII (July, 1918), pp. 36–40.

overbalance their higher content of light original material.[1] It was recognized, however, that the inquiry could not be regarded as having covered all the shrinkage phases of this mass-effect until the physical states of the four bodies during their formation were considered. Under the planetesimal hypothesis their formation embraced two phases: (1) the progressive concentration of those portions of the solar outbursts that were held together by their mutual attractions so as to act as unit assemblages and thus serve as collecting centers or nuclei; (2) the gathering into these nuclei of such scattered parts of the solar outbursts as were dispersed into planetesimal orbits from which they could be picked up only individually. The first process started with a gaseous body and followed the gaseous line of descent; the second was concerned with individual bodies and orbital dynamics. This paper is confined to the first of these.

THE SUCCESSIVE PHYSICAL PHASES ASSUMED BY THE NUCLEI IN PASSING FROM THEIR ORIGINAL CONDITION TO THEIR FINAL STATES AS PLANETARY CORES

There is a wide range between the largest planet and the smallest planetoid. There may also be wide differences of view respecting the probable sizes of the nuclei. As I wish to leave the question of the nuclear masses freely open for the present, it seems best to treat broadly the whole group of solar dependents, including planets, planetoids, and satellites. There is the additional reason that their gradations, their likenesses, and differences, as well as the contrasts of their extreme developments, form the natural background for the special cases with which we are particularly concerned in this discussion.

It is assumed that each one of the present planets, planetoids, and satellites started from a nucleus inherited from a solar outburst. It is held that some of these nuclei were formed from the central portions of the solar outbursts, while others were merely segments detached from these. Some of the detached segments are supposed to have remained under the control of the central portions and become satellites, while others pursued orbits of their

[1] "Selective Segregation of the Earth and Its Neighbors," *Jour. Geol.*, Vol. XXVIII (1920), pp. 126–57.

own and became planetoids. These are regarded as natural results of solar eruptions under exceptional stimulus from a passing body.[1]

As the assigned result of this there arose a very significant series of solar attendants of cognate birth and linked together by gradations, though the extremes were quite highly differentiated. The series, as now presented, ranges from massive hot gaseous planets of low densities, down through intermediary forms, to quite small solid bodies of high densities and altogether devoid of appreciable atmospheres. In mass value the largest planet is several million times the smallest planetoid—probably we could say several billion times, if the lower limit of the planetoids were accurately determined. In Table I this great series is listed in the order of size, neglecting the common distinction between planets, planetoids, and satellites, which is immaterial in this particular study. The physical differences are brought out by groupings. It will be seen that the planets, planetoids, and satellites are notably mixed in the lower part of the list. The gradation would doubtless be much closer and the classes even more intermixed, if the sizes of all the smaller bodies were well enough determined to permit a strictly accurate arrangement of the smaller masses. There are now known to be 26 satellites and upward of 800 planetoids, most of which seem to be less than 100 miles in diameter.

While in general there is a notable gradation, there is yet a wide gap between the giant group of gaseous planets and the terrestrial group next below, which are essentially solid but have gaseous envelopes. Within the latter group a somewhat notable difference in mass sets off the earth and Venus from Mars. The scant atmosphere of the last allies it to the atmosphereless group below and its nucleus not unlikely belonged to that class.

The differences in the groups suggest that the formative processes, though of the same type and initiated in the same way, entered in such different proportions into the actual formative work that they gave rise to very divergent results. This tallies with our earlier suggestions that the formative agencies embraced within

[1] See the special cases of May 29 and July 15, 1919, outlined in this *Journal*, Vol. XXXVIII (February–March, 1920), pp. 145–49, or the original description by Pettit, in *Astrophys. Jour.*, Vol. L (October, 1919), pp. 206–19.

themselves opposing factors (VII of previous article)[1] so poised as to permit a ready shifting of dominance from one side of the

TABLE I

THE SOLAR DEPENDENTS GRADED BY SIZE AND GROUPED BY PHYSICAL PROPERTIES

A. THE GIANT GROUP. HIGHLY GASEOUS BODIES

(Densities low; diameters between 30,000 and 90,000 miles)

	Densities	Diameters in Miles
Jupiter	1.25	88,392
Saturn	0.63	74,163
Neptune	1.09	34,823
Uranus	1.44	30,193

B. THE MEDIAL OR TERRESTRIAL GROUP. SOLID BODIES BEARING ATMOSPHERES

(Densities high; diameters between 4,000 and 8,000 miles)

	Densities	Diameters in Miles
Earth	5.53	7,918
Venus	4.85	7,701
Mars	3.58	4,339

C. THE DIMINUTIVE GROUP. ATMOSPHERELESS SOLID BODIES

(Densities high; diameters ranging from 3,600 miles down to the lower limit of estimating power)

	Bodies	Diameters in Miles
Satellite	Jupiter's III	3,558
Satellite	Jupiter's IV	3,345
Planet	Mercury	3,009
Satellite	Saturn's VI	3,000

THE DIMINUTIVE GROUP—*Continued*

	Bodies	Diameters in Miles
Satellite	Jupiter's I	2,452
Satellite	The Moon	2,100
Satellite	Jupiter's II	2,095
Satellite	Saturn's VIII	2,000
Satellite	Neptune's VIII	2,000
Satellite	Saturn's V	1,500
Satellite	Saturn's III	1,200
Satellite	Saturn's IV	1,100
Satellite	Uranus's I–IV	500 to 1,000
Satellite	Saturn's II	800
Satellite	Saturn's I	600
Satellite	Saturn's VII	500
Planetoid	Ceres	485
Planetoid	Pallas	304
Planetoid	Vesta	243
Satellite	Saturn's IX	200
Planetoid	Juno	118
Planetoid	Several exceeding	100
Satellite	Jupiter's I	100
Planetoids	Probably 700 or more, ranging downward from	100
Satellite	Mars's II	...
Satellite	Mars's I	10
Satellite	Jupiter's VI and VII	"small"
Satellite	Jupiter's VIII and IX	"very small"

Planetoids. The smallest order of planetoids probably form the lower end of the series, ranging down to 10 or perhaps even 5 miles.

balance to the other, thus giving rise to a series of widely varying effects which at the extremes even became contrasted. The preponderance in the upper end of the series lay markedly on the

[1] "Selective Segregation of Material in the Formation of the Earth and Its Neighbors," *Jour. Geol.*, Vol. XXVIII (1920), pp. 126–57.

side of gas accumulation, while in the lower part the dominant effect lay in the dissipation of all gas. In the middle ranges there was a closer approach to equipoise between these extremes and hence to a mixed product of the medial order. It is thus clear that the genetic processes, however alike basally, were capable of giving such different results as to make it necessary to study with care and patience the balancings between opposing influences and the differential effects of the shifting of these balances.

THE CRITICAL CONDITIONS THAT CONTROLLED THE PASSAGE OF THE NUCLEI INTO COLLECTING CORES

The original diversity of the nuclei is assigned to differences in the impulses imparted by the solar eruptions. The evolution of the nuclei, after being launched on their several careers, was critically dependent on the dynamic properties which they inherited individually. These now require attention. We need not dwell, however, on the giant gaseous planets, for they do not fall within the range of our present problem, nor do they seem to have ever passed through the more critical phases of the processes we are about to consider. They probably had, at the outset, nuclei massive enough to hold essentially all their own gases in spite of their molecular activity and to retain essentially all alien molecules that plunged into them.[1]

To cover the whole field of the known solid bodies in a representative way, Table II is introduced. It gives certain essential dynamic properties for ten typical bodies, four natural and six ideal, so selected as to represent at convenient intervals the whole range from the earth—the largest known solid body—down to a ten-mile planetoid. Dr. W. D. MacMillan has been kind enough to make the computations for this table.

It seems improbable that the nuclei of the earth, Venus, Mars, or the moon, even at their smallest stages, were so diminutive as the lower orders of ideal bodies in Table II, but these very small bodies are even more serviceable than larger ones in illustrating the critical conditions that attended their formation and measurably that of

[1] The inevitable loss of such molecules as attained very exceptional speeds is neglected throughout this discussion.

the larger bodies of the solid order. They thus serve to put to severe test our notions as to the formation of such bodies. It will not be surprising if we find that these small bodies lie on the precarious border that separates successful aggregation from dissipation into planetesimals.

TABLE II

DYNAMICAL PROPERTIES OF TEN REPRESENTATIVE BODIES OF THE TERRESTRIAL AND SMALLER CLASSES

THE TEN BODIES		STATISTICAL PROPERTIES			DYNAMICAL PROPERTIES			
a No.	*b* Name	*c* Diam. in Miles	*d* Density Water = 1	*e* Mass Earth = 1	*f* Surface Gravity *g* = 1	*g* Parabolic Velocity in Miles per Sec.	*h* Velocity of Retention in Miles per Sec.	*i* Diameter of Sphere of Control
I.....	Earth	7918	5.53	1.0000	1.00	6.95	4.91	1,240,000
II.....	Venus	7701	4.85?	0.807?	0.85	6.33	4.48	1,156,000 (836,000)
III....	Mars	4339	3.58	0.1065	0.36	3.06	2.16	588,000 (898,000)
IV.....	Ideal	3407	3.50	0.050	0.27	2.38	1.68	458,000
V	Moon	2160	3.34	0.0122	0.16	1.47	1.04	286,000 (50,000)
VI.....	Ideal	1000	3.30	0.001202	0.075	0.68	0.48	132,000
VII ...	Ideal	500	(*a*) 3.30	0.0001503	0.0375	0.34	0.24	66,000
			(*b*) 5.00	0.000228	0.057	0.42	0.30	76,000
VIII...	Ideal	100	(*a*) 3.30	0.000001202	0.0075	0.068	0.048	13,200
			(*b*) 6.00	0.000002186	0.0137	0.123	0.087	16,000
IX....	Ideal	50	(*a*) 3.30	0.0000001503	0.00375	0.034	0.024	6,600
			(*b*) 6.50	0.0000002960	0.0074	0.067	0.047	8,200
X.....	Ideal	10	(*a*) 3.30	1.202×10^{-9}	0.00075	0.0068	0.0048	1,320
			(*b*) 7.00	2.550×10^{-9}	0.00160	0.0144	0.0102	1,700

The selections are adapted to the earth as unit and the spheres of control are based on the earth's distance from the sun. An ideal body $\frac{1}{20}$ the mass of the earth is introduced between Mars and the moon to better grade the series, and for a like reason an ideal body 1,000 miles in diameter is introduced below the moon. The four ideal bodies, 500, 100, 50, and 10 miles in diameter, respectively, are selected to cover the range of the planetoids and smaller satellites. The largest of planetoids thus far measured satisfactorily is 485 miles in diameter (Barnard). Two hypothetical densities are assigned to each of these, the one to represent bodies supposed to be composed largely of stony matter, the other to represent those that may have a notable content

of iron. In the 10-mile body this higher density is put at 7, which is thought to be as dense as any such natural aggregate, inevitably more or less mixed and porous, would be likely to be.

Column *f* gives the maximum acceleration of gravity at the surface of the given body, stated in percentages of the acceleration of gravity at the surface of the earth. Column *g* gives, in miles per second, the parabolic velocity (= velocity required to give to a projected body a parabolic path = velocity capable of carrying a body to infinity = velocity acquired in a free fall from infinity = "velocity from infinity"). In discussions of the limitations of atmospheres, this "velocity from infinity" has very commonly been used erroneously as "the critical velocity of escape," but by referring to column *i* it will be seen that a molecule shot away from these bodies may reach the limit of the body's control very much short of an infinite distance. If one wishes to show that the molecules *must escape*, and desires to make his statement conservative by leaving a good "margin of safety" to cover defects in data and otherwise, the parabolic velocity is a very suitable criterion to use. If, on the other hand, one wishes to show that molecules *will be retained*, and desires, as before, to leave a margin of safety for retention somewhat above that, the figures in column *h* form convenient criteria. Strictly speaking, these represent the velocity required to give a particle a circular orbit at the surface of the body, and this velocity forms a dividing line between the ordinary collisional atmosphere and the orbital ultra-atmosphere. The latter forms the transition stage through which molecules may escape from control with the least velocity. The velocity in a circular orbit has a fixed ratio to the parabolic velocity for the same point, viz., $1:\sqrt{2}$. The figures for the parabolic velocity and for the velocity of circular orbit or "velocity of retention" each becomes lower as the points of reckoning rise above the surface. The minimum velocities required for escape lie between the velocity for circular orbit and the velocity of fall from the limit of the sphere of control and are dependent on the mode of escape.

Column *i* gives the diameters of the spheres of control of the several bodies in competition with the sun *at the earth's distance*. It is important to note the qualifying clause, for spheres of control vary with the distance from the controlling body. The *actual* spheres of control of Venus and Mars are given in parenthesis. For the present discussion spheres of control at the distance of the earth are most serviceable. In the case of the moon, the figure in parenthesis represents the moon's sphere of control *as against the earth*, within whose sphere of control it revolves.

It is worthy of note that the spheres of control at the lower end of the series, notwithstanding their diminution, still have notable dimensions. These spheres of control give concrete pictures of the areas over which the several bodies exercise collecting as well as holding power, while the figures in columns *g* and *h* give data for realizing, in terms of velocity, how limited is the power of this influence in the smaller masses.

The table would be additionally helpful if the central pressures, the central densities, and the central temperatures could each be given in terms equally trustworthy, but determinations of these properties rest on a much less secure basis. The central pressures can only be determined by assuming some law of downward increase of internal density. The actual rate of such increase is uncertain, beyond the fact that it must fall within certain rather broad limits defined by precession and other astronomical phenomena whose requirements are not precisely determinable. Laplace's theoretical law of density is perhaps the most plausible and is the one commonly used in preference to such others as have been proposed. Using it, MacMillan finds the central pressure of the 10-mile body, when assigned a mean density 3.30, to be only 11.8 lbs. per square inch, i.e., less than the pressure of the earth's atmosphere. On the other hand, that of the present earth is 22,500 *tons* per square inch, or about 3,000,000 atmospheres. The results given by Laplace's law are in general accord with those obtained earlier in this discussion from a comparison of the moon, Mars, Venus, and the earth.[1] However, reserve in placing implicit confidence in this law is to be observed, for by carrying the series of determinations upward from the earth on the same basis, MacMillan finds that at a radius of about 5,000 miles the central density becomes infinite. This seems to mean either that the law breaks down or else is rendered inapplicable by some intercurrent factor whose nature is as yet unknown. Dr. A. C. Lunn reached results of similar import in his geophysical studies under the planetesimal hypothesis in 1909.[2] The suggestive correlation of the densities of the whole series of planets made by MacMillan in his paper "On Stellar Evolution" deserves thoughtful consideration in this connection.[3]

It is clear, then, that until some elucidation is found for this singular result so shortly reached after the dimensions of the earth are passed, it is unsafe to build important conclusions upon the law.

[1] "The Order of Magnitude of the Shrinkage of the Earth Deduced from Mars, Venus, and the Moon," *Jour. Geol.*, Vol. XXVIII (1920), pp. 1–17.

[2] "The Tidal and Other Problems," *Carnegie Publication No. 107* (1909), pp. 201–2.

[3] *Astrophys. Jour.*, Vol. XLVIII (July, 1918), pp. 36–40.

In reaching conclusions respecting the central temperature there is not only the danger of error due to deducing it from compression computed according to this doubtful law, but there are other sources of uncertainty, among which one of the more serious is the unknown amount of heat removed by inherited eversive movements within the body, co-operating with ordinary convection while the formative processes were in progress, and since. In the distinctly large bodies these might not perhaps rise to decisive value, but in the smaller orders of bodies the central temperature theoretically assignable to concentration might be so far dissipated by the combined effects of inherited eversive movements, convection, conduction, and viselike mechanical action (discussed below) that it would have but limited effect on the physical state of the core into which the nucleus passed.

A further serious difficulty in estimating central temperature arises from our ignorance of what part of the potential energy theoretically set free by compression went into endothermal reorganizations, what part became latent in forming solutions, what part was carried surfaceward by the forced ascent of these solutions, and what remained to increase the temperature.

THE GROUP OF FACTORS THAT CONDITIONED THE PROCESS OF NUCLEAR CONCENTRATION

The passage of the planetary nuclei from their original states as solar gases into their final states as the cores of planets, planetoids, and satellites was by no means so simple a process as gaseous condensation has usually been regarded. Beside the simple condensing process, as usually considered, there were co-operating activities that radically modified the general tenor of the process. Four of these require consideration:

I. *Several types of motion were inherited from the solar eruption, and these took the lead in determining the internal circulation. The thermal convection, as it arose, was superposed on these.*

II. *A sifting of the mixed molecules of the original gaseous matter set in almost as soon as it emerged from the sun and changed the mixture to the proper proportions for forming planetary cores.*

III. *The formation of precipitates also set in early, and gradually changed the primitive gases into Brownian mixtures which themselves*

changed as time went on. In the smallest order of bodies this precipitation, together with the escape of such molecules as remained free, went so far ultimately that the residues were reduced to clouds of precipitates which condensed in a way of their own.

IV. *Almost as soon as cores began to form, differential stresses, more intense below than above, were brought to bear upon them by external agencies which aided in working the lighter and more mobile materials toward the surface, thus developing increasing density and solidity in the central parts.*

In discussing these co-operating factors it will be helpful to have in mind concrete pictures of the deployment of the matter under study, fashioned in the form of spheres of control, for these best bring out the dynamics of the organizing work. The matter in spheres of control may be very differently distributed, but it is to be regarded as occupying in some measure, however scant, the whole space. In adult organizations, usually the matter is highly concentrated toward the center and very sparsely distributed in the outer part. In the initial stages the distribution is likely to be heterogeneous with less difference between the outer and inner parts. Uniform distribution therefore becomes the most convenient standard of reference, though probably never realized in fact. Table II gives data from which selections may be made at pleasure in forming representative pictures.

The primitive earth-mass, before sifting began, should have included (1) the light gases that later escaped and were never recovered, (2) the planetesimals that temporarily escaped and were later recovered, (3) the nuclear portion that remained under self-control, and (4) minor factors that may be neglected. Let the whole be taken as having a mass about twice that of the present earth, without prejudice to a higher or lower final estimate. It would then, if properly distributed, have a sphere of control of the order of 1,500,000 miles in diameter and a mean density for the whole sphere of about 0.0011 on the air standard, or, let us say, approximately 1/1,000 of the density of the air at sea-level. As loss by sifting went on the sphere of control should have shrunk to a minimum, after which, when planetesimal accretion began to

overmatch the molecular escape, it should have grown to its present size. It is not best just yet to try to decide what this minimum may have been, but let it be placed as low as $\frac{1}{10}$ of the present mass of the earth to make the gap between our two pictures wide. Its sphere of control would then have approached 500,000 miles in diameter and the mean density for the whole sphere .0011, on the air standard. The spheres of control are here computed on the supposition that the matter in each case is distributed in spherical form and that each concentric layer is homogeneous. Actual spheres of control are not strictly spherical and the distribution of matter at least in the early stages was probably not homogeneous. The figures given are themselves only convenient approximations, but they serve well enough to indicate the general order of tenuity. Only gravitative attraction is taken into account. The phenomena of comets' heads imply that there is a supplementary force in such very diffuse bodies, perhaps electromagnetic, but that may be regarded as merely a "margin of safety" in this discussion.

Among the points to be noted, though they cannot be discussed here, are: (1) the high degree of tenuity, which gives some notion of the extent to which matter may control itself in the terrestrial part of the solar domain; (2) the temperature produced by the expansion of the solar gases to this degree of tenuity; (3) the facilities for radiation afforded by this tenuity; (4) the nature of the internal movements in such tenuous bodies.

I. *The motions inherited from the solar eruption and their co-operation with convection in modifying the condensation of the nuclei.*— The gaseous matter erupted from the sun inevitably carried into its new activities some measure of the turbulence that previously affected it, while the forces of ejection added to this their own differential impulses. In so far as these impulses had uniform effects on all parts of the erupted mass, they merely served to send the whole out into its orbital course. This does not specially concern us here, but we may note in passing that the uniform increments of motion discovered by Pettit in the solar eruptions of May 29 and July 15, 1919, seem to be singularly felicitous factors in promoting projection into orbits without those high tendencies

to dispersion naturally assigned to simple explosion and that would be unfavorable to self-control.[1] We are here concerned only with those differential impulses that affected the relations of one part of an ejected mass to other parts. It is assumed that these differential impulses were so graded that (1) they scattered into planetesimals a notable part of the projected mass, (2) they tore away from the central portions segments that were massive enough to hold themselves together, but not very firmly, while (3) the main central masses retained a higher degree of self-control.[2] Such a partition of effects seems the natural result of the mechanics of eruption. It seems also to fit the requirements of the bodies that now make up the planetary system. The masses that retained their self-control were the nuclei of the organizations that were to follow, and constitute the theme to which we are here confined.

Under such a range of impulses the nuclei probably graded from the largest and most strongly held down to small diffuse ones on the very limit of self-control, beyond which complete dissipation into planetesimals set in. They are therefore to be dealt with as a graded series rather than a single type. The question of control, however, was not so much a matter of mass as of balance between the force of gravity and of the motions involved.

Three types of inherited motions need recognition: the turbulent, the vortical, and the rotatory. Turbulent motions were not only inherited directly from the sun, but must have been generated by unbalanced thrusts and drags incident to eruption. Eruptive actions almost inevitably give rise to more or less of vortical motion, or at least some form of eversive motion. In free interplanetary space, and in such tenuous bodies as those under discussion, motions of this type might persist long and be specially effective in discharging internal heat. All unbalanced differences of thrust and drag in the ejection of erupted masses would ultimately appear in the form of rotation and so rotation of some order could scarcely have failed

[1] *Jour. Geol.*, Vol. XXVIII (February–March, 1920), pp. 145–49, or the original article by Pettit, *Astrophys. Jour.*, Vol. L (October, 1919), pp. 206–19.

[2] In addition, the least projected parts fell back to the sun, while doubtless some particular parts received cumulative impulses and were thrown into anomalous courses, but these are neglected throughout this discussion.

to be inherited from the ejection. The amount of this primitive rotation, however, is not deducible directly from such rotations as the bodies now have, for the present rotations are assignable chiefly to the effects of planetesimal infall after the nuclei had become planetary cores. This later effect was conformable to a law of equilibrium under which the rotations were sometimes accelerated and sometimes retarded.[1]

When these inherited motions were strong enough to cause dissipation, the nuclei of course vanished into planetesimals, but when they were mild enough to be consistent with control, they became vital factors in the process of concentration. The normal system of thermal convection was gradually developed later and hence had to conform to the inherited motions already in control of the matter. In large nuclei the convectional motions might come in time to dominate the inherited motions, but in the smaller diffuse nuclei that were more quickly cooled it perhaps never came to be more than a secondary factor. At any rate, the dependence of the convective circulation on the inherited motions—merged mainly into rotation later—must have given rise to a distinctly gyratory system of circulation. This doubtless had some analogies with the circulations of the atmosphere and of the ocean, which, though essentially thermal, are profoundly affected by the earth's rotation. A fundamental difference, however, needs notice. We are here dealing with hot bodies whose radiation is primary. The surface of a rotating body has its greatest convexity transverse to the equator, while the polar surfaces are relatively flat. The greatest radiation in proportion to the immediate submass therefore takes place in the equatorial region. In addition to this the escape of molecules is aided by the centrifugal component of rotation, which is greatest at the equator and sinks to zero at the poles.

It has already been noted that escaping molecules carry off thermal energy in relatively high amounts. The escape of molecules may then be regarded as a form of quasi-radiation. It is, therefore, a rather firm inference that the equatorial belt is the most effective cooling tract of a hot, rotating body, though this may easily be masked by the high radiation from all surfaces.

[1] *The Origin of the Earth* (1916), p. 99.

It is a notable fact that the equatorial belts of the sun, Jupiter, and Saturn rotate faster than portions of their surfaces on the same meridian in higher latitudes. This has been the subject of much speculation and has received different explanations, more than one of which may contain a measure of truth. One suggestion is that it is due to the infall of planetesimal matter. A closely allied suggestion is that it is due to the falling back of matter ejected from the sun into the planetary regions and drawn forward in the direction of their motion, so that on returning it carries surplus momentum acquired from the planets. These are not inconsistent with the suggestion here made that part of the acceleration may be merely a phase of circulation normally set up in such hot rotating gaseous bodies. In a hot fluid body of the volume and rate of rotation of the earth, a mass, cooling and sinking from the equatorial surface, would—if it were free from contacts with surrounding matter—acquire an orbital velocity before it reached the center, and hence would sink no farther because the centrifugal component of its motion would wholly offset the pull of gravity upon it. If forced below that depth, its centrifugal component would act as a buoyant force. Of course, the sinking mass never would be free from contacts, and so it would necessarily exchange energies with the contact matter. The sinking mass would thus act as an accelerating undertow for any matter that flowed in above it as it sank; so also it would tend to drag forward whatever was in contact with it on its sides and below. It is not difficult to work out a system of circulation actuated by such equatorial cooling and sinking. It would, however, undoubtedly be subordinate to the intimate turbulence that would spring from other factors. The axial tract would present a unique problem, for it would be little affected by rotation and would not directly be reached by the descending equatorial currents, for they would be restrained by the centrifugal component of rotation and turned northward and southward, completing their circuits by return from the higher latitudes with such deflections as rotation imposed. This part of the circulation may be pictured as two vortex rings made up of spiral submovements trending downward on their contact sides at the equator and upward on their poleward sides. The axial tracts in themselves

would seem to invite a more direct and simple convection, but they might be specially subject to influence from the inherited motions. For example, if the rotation were west-east, like the sun's rotation in which the mass participated before ejection, and there were a north-south axial movement as in the case of the eruptions of May 29 and July 15, 1919, cited above, there might naturally be inherited from this an axial movement from one pole through the center to the other. The original tenuous state would apparently be favorable to this, and, once established, it might be perpetuated as an effective form of central convection. A special interest attaches to this from its possible influence on the solid core as that gradually formed—but this cannot be discussed here.

The point to be emphasized is the inevitable subordination—in the early formative stages—of the convection actuated by difference of temperature to the inherited motions. The circulation, far from being simple descent and ascent, was tortuous and involved, and the core-forming process must be interpreted on this basis.

II. *The molecular sifting of the nuclei required to reduce the original solar gases to the composition of the present solid bodies.*—The nuclei of the giant planets may be passed by, merely remarking that there is little reason to think they suffered much sifting; rather they seem to have been so massive from the outset that they retained all classes of molecules that came under their control. By far the larger number of the solid bodies of the solar system, however, are practically devoid of free gases, and seem to be formed almost wholly of stony and metallic matter. None of the terrestrial planets carry more than a very small percentage of free gases; apparently almost their whole substance consists of stony and metallic materials such as make up the main body of the earth and of meteorites.

The original gases of all the bodies derived from the sun, large and small alike, should have had essentially the same composition. Spectroscopic analysis shows that the visible substance of the sun is an intimate mixture of many kinds of molecules. Unfortunately, their relative proportions can merely be inferred in a general way. The low density of the sun (1.40), notwithstanding its great mass, implies—even when its high temperature is considered—

that the lighter elements form a notable factor, and the spectroscopic evidence tallies with this. The low densities of the giant planets derived from the sun (Jupiter, 1.25; Saturn, 0.63; Uranus, 1.44; Neptune, 1.09) suggest a similar constitution with even more cogency, for they are much less affected by high temperature. If, therefore, solid stony or metallic bodies of high specific gravity were to be formed from outbursts of solar gases, the process must have involved the removal of large quantities of the lighter order of constituents. This sifting is precisely what the kinetic theory of gases applied to small bodies would lead us to expect. The process is essentially a form of evaporation, and so the planetoids and satellites, as well as the terrestrial planets with slight qualification, may be regarded *as merely the residues of the selective evaporation of much larger original bodies of mixed gases.*

If the original gases, after they were projected from the sun, occupied some large part of the spheres they could control, as indicated above, the escape of the lighter molecules would be relatively easy and prompt, at least from the smaller masses. If the nuclei became much condensed before the sifting was completed, the remaining escape might be slow, for the molecules could then only escape from the outer zone where free paths were open to them when they chanced to rebound in an outward direction with the requisite velocity. In so far as the original gaseous masses were affected by turbulence, or by vortical or other eversive motions derived from their ejection, the escape of the light molecules would be facilitated.

The motions inherited from the original expulsion were probably such that the dominant tendency, in all but the more massive nuclei, was toward gaseous dispersion. Not only would the light molecules be likely to escape from control, but many of all kinds. This is only another form of stating the primary tenet of the planetesimal hypothesis, viz., that such dispersion was an inevitable effect of the solar eruptions, and a condition precedent to planetesimal accretion later. There is merely the reservation that enough material was held under self-control to serve as collecting centers of the requisite orders of efficiency, but even this is not essential to an ultra type of planetesimal genesis. It seems, how-

ever, to be definitely implied by a posteriori reasoning from the existing bodies. The present line of attack shows that the nuclei, except the four of the giant order, were little more than the residues of the heavier material left by selective molecular action working on larger original bodies of mixed gases. This seems to apply to all satellites, to all planetoids, and, in qualified degrees, to all planets from the earth downward.

The process of evaporation had the effect of reducing the energy of the residue per unit mass, and this, added to the inevitable loss by radiation, made control increasingly secure and caused loss to diminish till it became negligible.

III. *The formation of precipitates and of Brownian mixtures, grading into quasi-gaseous clouds of precipitate aggregates.*—As the original mixed gases emerged from the sun, expansion, abetted by radiation, must have promptly lowered the temperature, and this lowering of temperature doubtless led to the formation of precipitates. It is immaterial just here whether these precipitates were formed by simple cooling or by chemical action, or by both acting jointly. Nor is it of critical importance whether the precipitated particles were liquid or solid. It is highly probable that the earliest precipitates were formed of material such as later became the stony and metallic substances of the earth, of meteorites, and probably of all the small solid bodies. That such precipitates had begun to form even earlier is highly probable, for they are apparently now forming in the sun; at least the solar photosphere is commonly interpreted as a cloudlike zone of such precipitates.

At the outset such precipitates would necessarily be minute and diffusely scattered, for under the law of diffusion of gases the particular molecules that were precipitable at the temperatures existent at that particular stage would be distributed sub-uniformly throughout the turbulent mixture of molecules which formed the gaseous mass, but aggregation into granules, chondrules,[1] or other forms of concretions would doubtless at once ensue, after the analogy of the droplets and crystals of clouds.

[1] I venture to name chondrules here to suggest that conditions such as these are perhaps those most likely to have given rise to these singular little aggregates found in the majority of meteorites. They are commonly of the size of a millet seed, but range up to that of a walnut and down to dustlike fineness.

The minute precipitates thus scattered through the gas would serve as Brownian particles, and the increase of these would form a progressive series of Brownian mixtures. The minute precipitates would be jostled to and fro much as the free molecules were, except that, on account of their greater sizes and masses, they must have responded rather to combined molecular impacts than to single ones, while their lack of perfect elasticity must also have somewhat toned down these activities.

An analysis of the conditions makes it clear that the Brownian evolution probably diverged very soon into two rather distinct lines, though they must have been united by numerous intermediate phases. One of these may be regarded as the typal line of gaseous descent; the other as divergent toward an alien type that combined a quasi-gaseous phase with a partially orbital factor. In the first the characteristic feature continued throughout to be that of a jostling assemblage, though the original high proportion of molecules gave place more and more to precipitates acting as Brownian particles. The gas in this case is presumed to have passed into the liquid phase and thence into the solid form. In the more divergent line the assemblage lost its free molecules largely, and in the extreme cases entirely, and became at best merely quasi-gaseous, with a trend toward orbital behavior. Though truly gaseous at the start, the molecular assemblage soon began to be seriously depleted by the escape of the more active molecules and the passage of the rest into precipitates and thence into aggregates, while these tended to lose their to-and-fro dynamics and take on circulatory, rotatory, or revolutionary dynamics.

Divergent as these trends were, they were readily reversible. When molecules escaped from a nucleus in which their habit was strictly gaseous, they usually took on a specific orbital habit and beame planetesimals; the accident of an encounter, however, might easily throw them back into to-and-fro oscillation. Notwithstanding such reversals, two quite contrasted systems of dynamics arose and were continually contending with one another in the processes that marked the passage of the nuclei into cores.

The gaseous line of descent was obviously dominant in the nuclei of the giant planets. Perhaps it was also in the nuclei of the

earth and of Venus. But just how far down the scale it held its dominance may best be left an open question for the present. The considerations about to be offered imply that the second line of evolution was preponderant in the history of the small nuclei.

In nuclei massive enough and quiescent enough to maintain high internal temperatures it seems probable that the precipitates would generally pass from the gaseous state directly into liquid droplets which would serve for a while as Brownian particles and gradually gather into liquid cores, which in turn would develop solid precipitates within themselves and ultimately collect into solid cores. In following this more typical line of gaseous descent, however, it is important to discard the old view that magmas are melts, and to replace it with the modern view, now well established, that magmas are mutual solutions. There are of course melts, and melts sometimes freeze, and so melting and freezing have some place in geological processes, but it is a rather trivial one compared with solidification by chemical processes. Even on the present surface of the earth, which for a hundred millions of years or more has been developing a temperature contrast between the exterior and the interior, simple refrigeration has little expression except in the form of thin crusts; the interiors of even surface lava flows or pools have solidified chiefly by crystallization brought about by saturation in the mutual solution. In a nucleus so conditioned as to sustain the progressive collection of a liquid core at its center by hot precipitates from enshrouding gases there is little ground for postulating even the trivial crust formation that takes place on lavas poured out on the present cold surface. Superficial refrigeration could scarcely have been more than a negligible process. Appropriate temperatures and pressures must of course have been very essential factors in core formation, but rather as imperative conditioning influences than as direct agencies. They were less intimate and ultimate factors than the chemical forces that served as the immediate actuating agencies.

Unfortunately, present knowledge of the precipitating processes deep within magmas is insufficient to predict with much confidence the history of even an ideal liquid core in a perfectly quiescent state, much less to forecast the solidification of a core actuated by

such a tortuous circulation as the case in hand seems really to involve. Inquiry should, however, at least be put on the right track by recognizing the later aspects of science and the physical realities of the case.

It is at least safe to say that isolated crystals are habitually formed *within* magmas, not merely on their surfaces. In addition to this it is particularly important to recognize that the order of formation of minerals in magmas is not that of their melting-points, but rather singularly at variance with it. Some of the minerals commonly formed earliest, as magnetite, apatite, and ziroon, are higher in specific gravity than the average minerals formed later, and these are generally higher than the liquid from which they were separated. It is quite reasonable to suppose, as leading petrologists do, that the heaviest order of minerals, at any rate, if not the majority formed, would tend to sink through the mutual solution. The actual effectiveness of this tendency must, of course, be dependent on the viscosity of the magmas, the vigor of the circulation, and other conditions. Whether the heavy minerals would remain solid and collect at once at the center or be redissolved in the depths and continue longer in the circulation is doubtless to be left an open question for the present. But this and other questions are to be considered *under the conditions of a tortuous circulation rather than those of a quiescent liquid*. The tendency of the circulation must certainly have been to equalize the temperature and to favor a slowly progressive precipitation affecting large portions, if not all of the mass, rather than the mere surface. The heavier precipitates might then rather plausibly be assumed to collect where the combined effects of current and gravity offered them the most available resting places. If so, a core shaped to fit such conditions seems more probable than a strictly symmetrical sphere.

If we turn now to the other type of nuclear evolution—in which the sifting action not only went to greater lengths, but the sifted residue was much more affected relatively by motions inherited from the expulsory action—it is well to recall at the outset that the range of cases stretches from the largest solid bodies notably affected by the sifting process downward to the very borders of

complete dispersion, such complete dispersion springing variously from inherited motions, from thermal convection, from molecular activity, or from divers combinations of these. If, as the naturalistic method insists, the solid bodies themselves are to be taken as the vestiges of the actual process, the observed range in size tallies with our previous suggestion that the limits which permit success along this line are actually reached in the existing series. Apparently our best method, then, is to consider the whole range for the sake of learning what were the inhibiting conditions at the vanishing end. We may then the better form an opinion of what probably took place nearer the middle of the great series where our interest chiefly lies. A naturalistic method is much to be preferred to a deductive treatment, for the latter is embarrassed by the multitude of possible assumptions. In pursuance of the naturalistic method let us seek some telltale feature that has been actually realized and make that our base of procedure. The series of atmosphereless bodies furnish such a base. They tell us within what bounds the inhibiting limit lay for such gases as form atmospheres. In passing through the actual conditions of evolution they have been stripped of all gases as light and active as nitrogen or oxygen. Further than this, they have maintained that condition since. The conditions must probably have been most exacting in the hot genetic stages, and there has been chance for recovery since. Their present condition, with some reservations, may be taken as an approximate indication of equilibrium conditions. The graded list in Table I giving the range of planets, planetoids, and satellites, from the earth down, may be found convenient here.

The case of atmospheric gases being thus approximately determinate, it remains to find at what stages the gases or vapors of such stony and metallic substances as make up the earth, meteorites and like bodies, would encounter their inhibitive limit. The basis for this lies in the fact that the molecular velocities of molecules vary inversely as the square roots of their molecular weights. The heavier we assume the molecules to be the more conservative our conclusions, so let us assume that the small nuclei were composed of molecules as heavy as those of the leading minerals in meteorites. The square roots of the molecular weights of the nine

minerals commonest in meteorites, including iron, are 10, 10.59, 12.49, 14.69, 15.87, 16.18, 16.49, 16.70, 18.38. These are to be compared with the square roots of representative molecules that are not held by the atmosphereless bodies. We may take the molecules of oxygen and nitrogen as representing these, the square roots of their molecular weights being 5.66 and 5.2, respectively. The high temperatures at which alone the stony and metallic substances occur in working quantities enter vitally into the case.[1] Making requisite computations, it appears that these heavier molecules would not be held under genetic conditions by the four lower orders of the bodies given in Table II. This seems to force the conclusion that the planetoids and smaller satellites were not formed in a purely gaseous way. As this is a rather radical conclusion it is well to note that the premises have not been strained to reach this result but quite the opposite. The bodies have been taken at their full present masses, whereas only their nuclei were really involved during the critical genetic stages. The molecules are taken in their present complex state, whereas in their volatile state they were quite possibly simpler and hence more active. The attractive power at the surface of the present cold concentrated bodies was used, whereas the attractions at the surface of the expanded gaseous bodies would be much lower. Other concessions to conservatism were made.

But this only excludes a direct or immediate formation by the gaseous method. It leaves open the question whether or not the cloud of precipitates into which the original mixed gaseous substances naturally passed could have completed the work. If so, the genesis might have lain in the alien line of gaseous descent, though not in that of strict gaseous formation.

It was noted earlier in the discussion that the gases of the stony and metallic substances must have begun to be precipitated soon after expulsion from the sun. In the small detached segments the precipitation must probably have gone on rather rapidly to com-

[1] I am under obligations to Dr. Fred. E. Wright, of the Geophysical Laboratory of the Carnegie Institution of Washington, for information and advice on points involved here, as also to Professor W. D. Harkins, of the University of Chicago. In the statements made I have endeavored to avoid all uncertain ground and leave everywhere a margin of safety.

pletion, and the work of aggregation into granules probably followed closely after. The conditions for the escape of the molecules that remained free would also be favored by the smallness of the bodies and the condensation of the precipitated portion. The escape of the free molecules would leave the precipitate aggregates with such internal motions as were inherited from the previous states. The last previous stage was that of a Brownian mixture whose internal motions did not differ radically from those of true gases, but the growing inelasticity must not be overlooked. The laws that would have governed the cloud of precipitates when first formed would not have differed very widely from gaseous laws. The inherited motions had, however, as we have seen, introduced a tendency toward an orbital development. In general the precipitated particles in a Brownian mixture so conditioned would not fall directly to the center even if an open path were provided for them; on the contrary they would pursue elliptical orbits about the center. By interference they would undoubtedly at length reach the center but only through a delayed course with consequent dissipation of energy.

Now the units—which at the start were perfectly elastic molecules—would by the precipitating and aggregating processes grow into granules many million times more massive, and in the process would become increasingly inelastic. By this change in the nature of the unit there would have arisen a wide gap between even the heaviest of the free molecules and the average spherules, granules, or chondrules into which the precipitates passed. The velocities of the latter would have been of so much lower order that there seem no good grounds to doubt that the main mass of the latter would be susceptible of control and continued concentration under conditions that would be quite prohibitive of control as free molecules.

The very process of molecular escape tended in itself to increase the gap between the units prone to escape and those prone to continue their concentration. In every collision from which a molecule escapes by rebound there is an equal reaction of the partner in collision in the opposite direction. The escaping molecule usually has the lesser mass and to give escape the rebound must

be outward; the reacting molecule or granule therefore rebounds inward. *The very process of dispersion was therefore mated with a concentrating process and the two divided their results between the forming of nuclei on the one hand and of planetesimals on the other.* On the residual side of the twin process the ultimate result was the formation of a cloud of precipitated granules from which all free molecules had escaped. The cloud of course had less mass than the previous mixed nucleus, but there was a proportionately larger reduction of dispersive activity.

In the light of this we need next to consider further the holding power represented by the spheres of control. The spheres of control in Table II are computed for the earth's distance from the sun. They would be relatively larger farther out and smaller farther in. By reference to the table it will be seen that the fields under control are by no means insignificant even for the smallest bodies represented. At the same time, reference to the adjoining columns of the table will show that the *strength* of control is distinctly limited. It is also to be noted that the velocities of retention and escape are given for the surfaces of the concentrated bodies as these now are, and that the velocities that can be controlled decline rapidly for points farther from the center.

Now expansion does not affect the simple static holding power so much as it does the velocity that can be controlled. Within the limits of the sphere of control, and with some other qualifications, simple expansion or contraction does not affect the extent of the sphere of control. It is a principle of celestial mechanics that if a body is spherical and if its substance is distributed either uniformly or in homogeneous concentric layers its gravitative effect on bodies outside it is as though the whole matter were concentrated at the center, and hence, of course, expansion or contraction is immaterial so far as relates to bodies on the borders and outside the body itself. If the body is not strictly spherical or homogeneous in concentric layers, the deduction will not strictly hold, but any departure will in general be measurably in proportion to the departure from sphericity or homogeneity, so that the principle may be used without radical error in respect to normal spheroids of revolution. Applying this deduction to the range of bodies rep-

resented in Table II, the sizes of the spheres of control will remain about as given whether the substance they contain takes the form of an expanded gas, or an open swarm of precipitated granules, or a compact solid body. This puts everyone in the way of modifying at pleasure the illustrations I offer.

To the concrete pictures already given the following may be added as now more immediately serviceable. From the minimum radius of the sphere of control of the earth, 620,000 miles, let a depth of 20,000 miles on the outer border be left essentially unoccupied and the whole present substance of the earth distributed uniformly throughout the remainder. It would have a density of 0.001266 on the air standard. In the form of a cloud of granules, each half the mean density of the earth, and distributed uniformly, the empty space about each granule would be over a million and a half times the space occupied by the granule itself.

If a 10-mile planetoid were converted into a cloud of granules uniformly distributed through its sphere of control, the cloud would have a density of 0.00111 on the air standard. If the granules had the same density as in the planetoid, the average empty space about each granule would be more than two million times the volume of the granule itself.

If therefore the clouds of granules were quite diffuse, they yet might be controlled by their mutual gravity, *provided* the dispersive components of their internal movements were negligible. But with such wide distribution any appreciable dispersive movements would be fatal to control.

To fashion a case of this order with a working margin of space, let the matter of a 10-mile planetoid of density 3.3 be dispersed uniformly as granules of like density throughout the central $\frac{1}{8}$ of its sphere of control, leaving the remaining $\frac{7}{8}$ as empty space which the granules must cross to escape. The density on the air standard would be 0.00889, while the average empty space surrounding each granule would be 280,000 times the volume of the granule itself. Even in this case the velocity at the surface that would give escape if directed outward would be perilously low, not above a fraction of an inch per second. This reveals the critical nature of all this class of cases. To insure success in final concentration, the

sifting process that preceded must have removed all constituents whose motions had any notable dispersing component; nor can any such component arise from mutual interaction without jeopardy. Almost the only line along which a body so small as a 10-mile planetoid could organize itself by the granular method seems to have lain in acquiring very early a higher central density and a less outward extension than that assigned. This might perhaps have been done by the reaction above noted. The peril of dispersion and the narrow margin of control in such cases lead to the conclusion that the smallest order of planetoids and satellites lie near—or perhaps quite on—the limit of possible genesis by even this divergent phase of the gaseous line of descent.

This conclusion tallies with the fact that no planetoids or satellites of the smaller order are known at the earth's distance from the sun, or within it. Bodies of this type appear only at the distance of Mars and beyond. The dynamic conditions of this inner region are perhaps too adverse for this type of formation. In the outer region conditions are notably less restrictive, but even there they undoubtedly put lower limits on the size of bodies formed by the gaseo-granular method of assemblage.

In the light of these considerations there seems little warrant for supposing that such bodies were ever formed in sufficiently great multitudes to have built up the earth or to have pitted the surface of the moon by their impacts. The number of lunar craters is estimated at 30,000. If each of these is the grave of an extinct planetoid, one might expect that a few living ones would have lingered to tell the story. The negative testimony of the heavens as to their existence in this region seems rather to favor the view that their restriction to the outer region implies that they are themselves witnesses to the limitation of this line of genesis in both place and frequency.

With the general lines and limits of nuclear evolution thus defined, our remaining task is to find the median places between the two extremes that fit the earth, Venus, Mars, and the moon. It is clear from the present state of these bodies that much sifting of the original solar gases was required, for while the earth, Venus, and Mars hold envelopes of gases of moderate molecular weight,

they do not hold hydrogen and helium, which abound in the sun in appreciable quantities. The sum total of the gases they do hold relative to the whole mass of these planets is very small. Even in the case of the earth, distinctly the most massive of the solid bodies, the sifting must have gone to very notable lengths.

It is not impossible that the nuclei of all four bodies were so far sifted down as to exclude essentially all the atmospheric gases, and as a result their concentration fell ultimately into the precipitate line of descent. On the other hand, it is quite possible that the earth and Venus had atmospheres of some moment at all stages. In the case of the moon, there seems no escape from the view that its nucleus could not have formed in gaseous fashion, for the moon does not even now hold an atmosphere. In its original hot diffuse state a mass of so low an order as the nucleus of the moon could only hold its material in the precipitate form. The atmosphere of the adult Mars is so scant that its nucleus probably had no appreciable atmosphere. It is doubtful whether Mars could even now, in its full-grown state, hold the atmosphere it has if the planet were heated to the point of volatilizing its stony substances. The cases of Venus and the earth seem so nearly on the border line that it is not unreasonable to take either view as the evidence now stands. Further study may turn the scales one way or the other.

So far as the shrinkage question is concerned, the matter narrows down to the possibility that the nuclei of the earth and Venus passed from their original gaseous states into planetary cores along the normal line of gaseous descent. If the main mass of the nucleus of the earth passed from the solar gaseous state into a central liquid magma and thence by chemico-crystalline action into a solid core, the process would have given special facilities for the adjustment of the matter in the interest of density. To that extent it would have forestalled later shrinkage that might otherwise have been recorded in diastrophic features. The *record* would not cover the full reality. The large amount of shrinkage deduced by our comparison of the moon, Mars, Venus, and the earth[1] would not be recorded even in the basal features of the earth's configuration. These studies, however, imply that the unrecorded

[1] *Jour. Geol.*, Vol. XXVIII (1920), pp. 1–17.

factor was not necessarily large relatively, even if the gaseo-molten phase of nuclear history did obtain and is given as generous an estimate as the data will warrant.

It ought not to be overlooked, however, that the solid core, in its assigned formation by the deposition of crystals or other precipitates from the gyrating currents of the central circulation, would have been very likely to have incorporated inequalities of material and taken on asymmetries of form so as to have presented a deformed foundation, as it were, for the later accretions. Such deformities would have been likely to have made themselves felt in the diastrophism of all that was built upon them. This is a phase of the subject which I hope to pursue further in the future.

IV. EXTERIOR AGENCIES THAT AFFECTED THE PLANETARY CORES DURING THEIR FORMATION AND AFTERWARD

The discussion thus far has been confined to agencies acting within the evolving masses. The evolution, however, was not free from influences that acted from without. One type of such action particularly requires consideration here, because it affected the successive adjustments and readjustments of material in the planetary cores. It will suffice to consider merely the case of the earth and the most typical agencies that affected it. The three agencies that lie back of changes of rotation, of nutation, and of the tides will sufficiently represent the whole. These agencies—and those of their kind here neglected—arose out of the same general processes as the planetary series itself and came gradually into function as the planets themselves took form. They were more or less effective at all stages thereafter. One special effect was to bring into play the resources that lay in the *mass-coherence* of solids, an essentially new element in the evolution.

The forces that produced the tides, the polar nutations and the changes in rate of rotation, not only caused changes of form that involved variations in the internal capacity of such inclosed spaces as there may have been, but caused differential stresses to permeate the growing cores from surface to center and call into action the viselike capabilities of stresses greater below than above. Those agencies which give rise to deformations of the

class known as zonal harmonics of the second order, such as the bulging of an equator and flattening of the poles, or the pulling out of polar cones and the flattening of the equatorial belt between, give rise to stresses much greater in the central parts than in the outer parts. Sir George Darwin[1] and others have computed these for an incompressible homogeneous earth and for certain compressible variations from this. In an incompressible homogeneous earth Darwin gives the differential stresses as bearing the ratios 8 at the center, 3 at the equatorial surface, and 1 at the poles. In a compressible earth the surficial stresses are relatively lower and those at the center relatively higher. For a certain compressibility the surficial stresses disappear and the central stresses rise $\frac{1}{6}$ in value.[2]

Now the main tidal stresses come and go every twelve hours and the subordinate tidal stresses at other and generally longer intervals. While relatively small, they are constantly acting in a given direction, and this presumably has a certain kind of cumulative effect. This effect is doubtless chiefly felt by such molecules of the interior as are under stress and are about ready to change their attachments and so are responsive to the influence of even small strains. It is coming to be recognized that such individual molecular activities constitute a notable factor in rock metamorphism, glacial motion, and other geological changes of a very intimate sort. This has been set forth by Leith[3] and other close students of the intimate nature of geological phenomena. Such persistent rhythmical oscillations of stress and strain as those of the tides seem well suited to aid effectually these individual molecular changes. The nutations of the poles represent pulsatory action whose periods are longer, but whose chief effects are probably of the same intimate sort.

Changes of rotation, however, represent action of a much higher order of power and much greater length of period. In deformative potency, rotation has a competency of the first order. Changes of rate of rotation were probably most active and effective while

[1] *Scientific Papers*, by Sir George Darwin, Vol. II (1908), pp. 476–81.

[2] *Ibid.*, p. 505.

[3] Leith and Mead, *Metamorphic Geology* (1905), pp. 173–76, and elsewhere.

planetesimal accretion was in progress. The earth core was then youngest and least compressed, and so probably least rigid and most susceptible to the influence of differential stresses. I have elsewhere shown that the changes in rotation were probably oscillatory about a medial rate in conformity to a law of equilibrium.[1] They may be regarded therefore as commanding influences both in respect to power and to the times and modes of application.

The elevated poles and depressed equator of the rhythmical tidal deformations were transverse to the elevated equator and depressed poles of the rotational changes, and this transverse attitude no doubt lent facility to the kneading action which their rhythmical periods brought to bear on the interior of the earth.

These co-operating agencies thus brought to bear on the whole interior of the solidifying earth a rhythmical series of differential stresses, most intense in the deeper parts and less intense toward the surface, and so admirably fitted to force the mobile and the lighter material toward the surface and to favor readjustments that brought about increased density and rigidity and probably also increased elasticity. It seems to me probable that this combination of strong mechanical stresses at distant intervals working with much gentler and more rapid rhythmical stresses has been the master-factor in controlling the secular reorganization of the earth's interior, a gradual reorganization which I think has been in progress from the time solidification began down to the present day. The normal result, as I see it, would be a general gradation of concentrative effects from surface to center—taking form in appropriate gradations of density, rigidity, and elasticity, also graded from surface to center. The results of our comparative study of the earth, moon, Mars, and Venus tally perfectly with this view and make it theoretically logical and consistent. The steadily increasing density from smaller body to larger body, in spite of the high probability that the smaller bodies inherited the heavier molecules, points very definitely to reorganization under the influence of compression. The oscillating differential stresses, greater below than above, seem peculiarly well suited to aid in working out the graded adjustments.

[1] *The Origin of the Earth* (1916), pp. 95–110, 172–79.

The cumulative evidences of recent investigations on tidal, seismic, nutational, and other phenomena support this view with little less than demonstrative effect. The most of these are now quite familiar. There is space here merely to quote the latest numerical determinations (1917) that have come to my notice. Schweydar,[1] as the result of observational, experimental, and mathematical work on the tides, the polar nutations, and the transmission of seismic waves, concludes that the earth conducts itself as though it had a mean rigidity $2\frac{1}{2}$ times that of steel, that the constant of rigidity at the surface is about 3×10^{11} dynes, that this increases in depth more rapidly than the density, so that at the center it reaches 30×10^{11} dynes, or ten times its value at the surface. The transverse seismic waves, as far down as the record permits a confident interpretation, indicate a definite gradation of density, rigidity, and elasticity. To insure that the total rigidity shall reach the mean value of $2\frac{1}{2}$ times steel, and at the same time be consistent with the rigidity known to prevail in the outer zone and the gradually rising rigidity implied by seismic waves as far down as their record is good, it seems clear that a high order of rigidity in the remaining central part is imperative. The old hypothesis of an iron core framed, among other reasons, to account for the high mean density of the earth—a purpose which it serves only clumsily—does not help much in meeting the still higher rate of rise of rigidity and elasticity toward the center, for iron is soft and malleable when hot. Nor does any special segregation of inherently heavy material in the earth, however helpful it may be in its place, fully satisfy the phenomena brought out by the comparative studies on the earth, the moon, Mars, and Venus. The whole evidence seems to point clearly to a systematic mass-effect, working on essentially the same material in all cases, aided, to be sure, but aided in only minor degree, by selective segregation. In the heart of the earth very likely the segregation of the metallic from the stony material has gone much farther than in the outer parts, but I see little reason to think the two classes of material have been wholly separated from one another. A segregation

[1] W. Schweydar, "Ueber die Elastizität der Erde," Sonderabdruck aus *Die Naturwissenschaften* (1917), pp. 1–27.

of the iron and allied metals into masses of moderate dimensions distributed through the stony material, after the fashion of the metallic and stony material in meteorites, would probably affect appreciably the transmission of transverse seismic waves, and so account for the peculiarities of the record of such waves as come through the heart of the earth quite as well as the assumption of a purely metallic core. An original mixed constitution from center to surface kneaded into the present solidity by differential stresses whose central intensity is to their surface intensity in about the same ratio as the central density, rigidity, and elasticity is to the surface density, rigidity, and elasticity seems to fit the requirements of the case.

NOTES ON THE MECHANICS OF GEOLOGIC STRUCTURES

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INTRODUCTION

Since an early date in the development of the science of geology it has been recognized that secondary structural features are the results of failure or yielding of rocks under deformative forces, and students of geology have attempted to interpret these secondary features in terms of the forces and movements which produced them. Because of the great size and heterogeneity of the earth masses involved, the analysis of the casual mechanics of a given major structural feature is never a simple matter. The geologist, not having witnessed the production of the structural features at hand, or of any similar features, finds it difficult to view the problem in perspective and in proper relationship to associated structural features.

Discussions of the mechanics of deformation in geologic literature on the whole indicate a rather elementary conception of the factors involved and a tendency to assume more or less arbitrarily a simple set of mechanical conditions, when the structures observed may be susceptible of several alternative explanations. A single structural feature or group of similar features is not necessarily indicative of the type of deformation involved. A group of intersecting faults may be looked upon as a sequence of unrelated events, when, with equal or better reason, they might be considered as essentially simultaneous and due to a single deformation. The two interpretations require a widely differing structural history of the region involved.

An open fissure obviously due to tensional stresses (so far as the fissure itself is concerned) may be an incident in simple elongation, shear, cross-bending, compression or shortening, or torsional

warping. A reverse fault implies conditions of shortening or compression but may in addition to this possibly be an incident in a general shearing movement, or a phenomenon of simple cross-bending, or may be due to torsional warping. A series of folds may be due to shortening or compression in a direction normal to the trend of the folds or to a general shearing movement in a direction at a considerable angle to the trend. In general the shearing type of deformation has been largely neglected in analyses of the mechanics of geologic structures, both fractures and folds.

It is in part the purpose of this paper to present the result of experimental work which illustrates the variety of mechanical explanations possible for a given structure, and incidentally to emphasize the extent to which many of these may be related to shearing, which the writer regards as an exceedingly common type of deformation in rock movements. It is further purposed to present and to illustrate experimentally analyses of the stresses involved in the various types of deformation.

DESCRIPTION OF APPARATUS

Several years ago the writer devised for use in the structural geology laboratory of the University of Wisconsin a simple type of apparatus for studying and demonstrating relations of fractures and of folds to the forces producing them. The apparatus is used in three forms as illustrated in Figures 1, 2, and 4. These are similar in construction, consisting of a rigid rectangular frame of gas pipe supporting two clamps between which a heavy sheet of rubber is stretched. One or both clamps may be moved in various ways by means of screws so that tension, compression, torsion, and shear, or combinations of these may be produced in the rubber sheet.

The medium in which fractures are produced is a thin coating of paraffin applied to the upper surface of the tightly stretched rubber sheet and chilled until it is brittle. The paraffin coat is best applied by pouring the melted paraffin very rapidly and freely over the rubber sheet, which has previously been warmed practically to the melting-point of the paraffin. The hot paraffin is allowed to drain from the rubber. A little experience soon

enables one to judge of the manipulation necessary to secure the thickness desired. The chilling can be accomplished by allowing cold tap water to flow over the uncoated side of the rubber. If chilled too rapidly or too much, cooling cracks will develop in the paraffin. Deformation of the rubber sheet produces systematic fractures in the paraffin bearing definite relations to the manner of deformation.

Folds are produced by coating the paraffin with a thin layer of plastic wax and laying smoothly over this a very thin sheet of rubber, such as is used by dentists, or a sheet of tinfoil. When the rubber thus coated is deformed, folds are developed in the plastic wax and its coating, as described later.

This type of apparatus has an advantage over the deformation of large masses of material in a compression machine of the piston type, as the forces are transmitted through the rubber and therefore applied at every point in the coating. The thin coat of paraffin may be considered as representing the flat-lying rocks in the zone of fracture, having wide lateral extent as compared with thickness. The sheet of rubber might correspond to the deeper zone of rock flowage. Deformation of the paraffin-coated rubber is comparable to deformation affecting the zone of flow and the overlying zone of fracture simultaneously. A distribution of stresses throughout the deformed mass is obtained. The phenomena of repeated faults or extensive systematic joining and of repeated folds much more closely simulate nature than do the single fractures obtained in a testing machine or the single folds which develop ahead of the piston in the type of apparatus employed by Willis and others.

An apparatus employing a stretched rubber sheet on which plastic layers were built up and deformed by the contraction of the rubber was employed by Alphonse Favre[1] in connection with a study of rock deformation. In order to apply the compressive force he attached wooden blocks to the rubber to serve as buttresses or thrust blocks. The net result was not essentially different from the results obtained by later investigaters employing apparatus of

[1] Alphonse Favre, *Archives des Sciences Physiques et Naturelles*, Nouv. Pér., Tome 62 (Genéve, 1878), pp. 193–211.

the type used by Willis. A slight modification of the apparatus of Favre was used by Hans Schardt,[1] who used various combinations of plastic and brittle layers in his studies of the mechanics of mountain building. Still another modification of Favre's work was employed by Stanislas Meunier,[2] who studied and described the fractures produced in a layer of partially set plaster on a contracting rubber sheet. These three investigaters confined their work to pure shortening and paid no attention to stresses set up by tension, shear, or warping.

FIG. 1.—Fractures produced by tension. A heavy sheet of rubber is held between two clamps and stretched by means of the screw at the end. It is then coated with paraffin which is allowed to chill until brittle, after which the rubber is further stretched by means of the screw, developing tension cracks in the paraffin.

EXPERIMENTAL RESULTS

Fractures produced by tension.—The apparatus (Fig. 1) consists of a frame with a rigidly attached clamp at one end and a movable clamp at the other which may be moved toward or away from the stationary clamp by means of a long screw. To develop tension fractures the rubber sheet fastened at its edges in the two clamps is tightly stretched by means of the screw and then coated with paraffin which is allowed to chill until brittle. Tension is then applied by further stretching of the rubber by means of the screw. A typical set of tension fractures thus developed is shown in Figure 1.

[1] Hans Schardt, "Études géologiques sur le Pays-d'Enhaut Vaudois." Troisiéme partie. A. Mécanisme des Dislocations. Chapitres xv–xvii. Planches VI–IX. *Bulletin de la Soc. Vaudoise des Sciences naturelles*, Vol. XX, No. 90, 1884.

[2] Stanislas Meunier, *La Géologie Experimentale* (Paris, 1899), p. 299.

These are approximately at right angles to the direction of movement as is to be expected. They are open cracks perpendicular to the rubber sheet. These results are what an analysis of the mechanics involved would indicate. The paraffin, like rock, is less resistant to tensional stresses than to shearing stresses. It fails, therefore, by the development of breaks along planes which are perpendicular to the maximum stress.

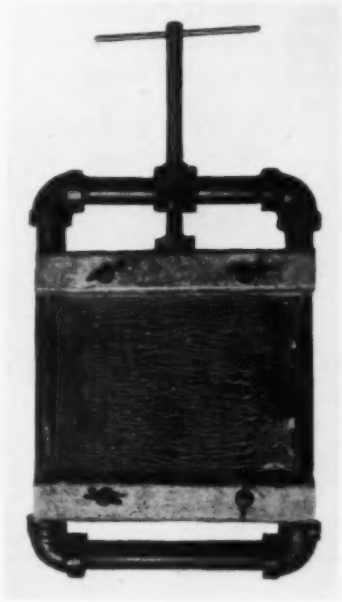

FIG. 2.—Fractures and faults developed by shortening or compression. This is the same apparatus as shown in Figure 1. The heavy sheet of rubber is first tightly stretched by means of the screw, coated with paraffin which is made brittle by chilling, after which the rubber sheet is allowed to contract by means of the screw, thus producing compressional stresses in the paraffin. Figure 3 shows these compression fractures in detail.

Fractures produced by compression.—The apparatus used for this purpose is the same as the one employed for tension. The compressive force is applied by releasing the screw and allowing the rubber to contract. This develops compressional stresses in the paraffin coat. The first breaks to appear are small inclined thrust faults striking at right angles to the direction of shortening and dipping approximately 45° either way. (See Figures 2 and 3.) These are followed by small number of vertical faults which strike at angles approximately 45° to the direction of shortening (seen near the margin of the rubber sheet in Figure 2) and are due to the fact that lateral relief is afforded at these points by the "spread" of the rubber sheet. There also appear a number of vertical tension joints striking in the direction of shortening and apparently due also to the "spread" of the rubber.

An analysis of the mechanics involved leads to conclusions in accordance with the foregoing experimental results. Under simple compression, fracture takes place by breaks which develop in the planes of maximum shear.[1] Therefore the paraffin should fracture along planes inclined at approximately 45° to the direction of the compressive force. The development of these inclined shear fractures requires actual displacement on the plane of fracture.

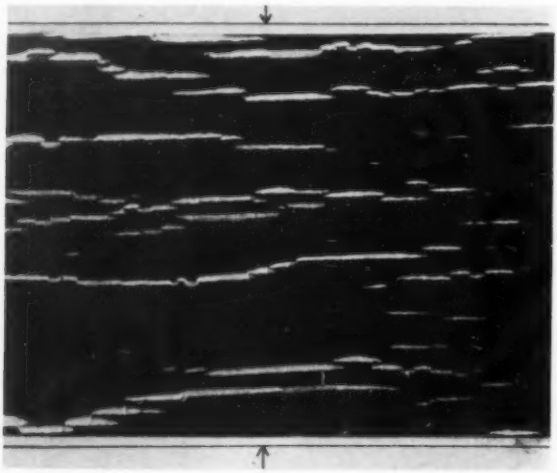

FIG. 3.—Fractures and thrust faults produced by shortening or compression in the direction of the arrows. (See Fig. 2.) The white bands are fractures and thrust faults in the paraffin which strike at right angles to the direction of shortening and dip at angles of approximately 45° in either direction.

This movement has a component parallel to the compressive force and also one at right angles to this force. Evidently, therefore, fractures can develop only in such an attitude as permits this movement to occur. In the central part of the rubber sheet the direction of easiest relief is upward or away from the surface of the rubber and therefore we expect inclined fracture planes striking at right angles to the direction of compression. Near the margin of the rubber sheet lateral relief is afforded, and we find

[1] C. K. Leith, *Structural Geology*, p. 16.

vertical fracture planes striking at angles of approximately 45° to the direction of compressive force.

This experiment in terms of earth movements is to be compared with a tangential shortening of an earth mass extending down into the zone of flowage, accompanied by side flowage or spread. This shortening is communicated to the rocks in the zone of fracture, resulting in inclined thrust faults striking normal to the direction

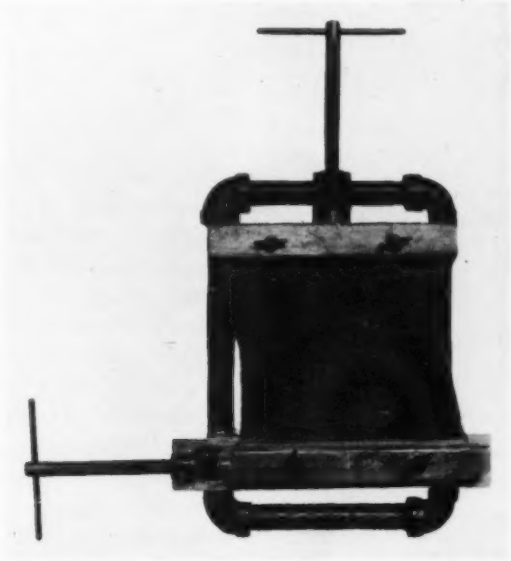

FIG. 4.—Fractures and faults developed by shear or rotational stress. A heavy sheet of rubber is tightly stretched between the two clamps by means of the screw at the top and coated with a thin coat of paraffin which is made brittle by chilling. The paraffin-coated rubber sheet is then deformed by means of the screw at the left. The fractures developed by the shearing movement are shown in detail in Figure 5.

of shortening, vertical shear faults striking at angles of approximately 45° to the direction of shortening and vertical tension joints striking in the direction of shortening.

Fractures produced by shear or rotational stress.—The apparatus used for this purpose is shown in Figure 4. It has one clamp

which may be moved toward or away from the other by means of a screw. The other clamp is mounted in a slide and by means of the second screw may be moved at right angles to the direction of movement of the first clamp. The sheet of rubber is tightly stretched between the two clamps, coated with paraffin, and deformed by means of the screw attached to the sliding clamp. This subjects the rubber sheet and its coat of paraffin to a shearing or rotational stress. The resulting fractures in the paraffin are shown in Figure 5. The direction of movement is indicated by the arrows and the amount of movement by the shape of the parallelogram which was, previous to deformation, rectangular.

FIG. 5.—Fractures produced in paraffin coat on rubber sheet by shearing. The arrows indicate the direction of movement and the shape of the figure shows the amount of distortion.

The first fractures to appear in any one locality on the rubber sheet are usually tension cracks inclined about 45° to the direction of the shearing movement. These are at right angles to the direction of maximum elongation and appear as vertical open cracks. They are followed immediately by two sets of vertical faults with horizontal displacement, one set striking parallel to the direction of movement and the other parallel to the free edges of the rubber sheet. These represent two directions of non-distortion or two shear planes developed by the shearing movement in which direction of relief is in the plane of the paraffin layer. Another set of faults, only two of which are shown in Figure 5, are thrust faults striking approximately at right angles to the tension crack and inclined approximately 45° dipping in either direction. These are due to

compression in a direction at right angles to the direction of maximum elongation.

The pattern of fractures developed in a series of experiments with varying thickness of paraffin coat is uniform in so far that the foregoing described set of fractures are always found. Their relative prominence, however, varies with the thickness and brittleness of the paraffin coat.

FIG. 6.—Fractures produced by torsional warping. A heavy sheet of rubber is tightly stretched between the two clamps by means of the screw, and coated with paraffin which is made brittle by chilling. Then the lower clamp is rotated by means of the handle at the lower end. This subjects the rubber sheet to torsional deformation and develops cracks in the paraffin. (See Fig. 7.)

Fractures produced by torsional warping.—It is difficult to form any estimate of the importance of this type of deformation, but it seems probable that torsional warping occurs and, therefore, that it merits consideration as one of the types of earth deformation.

A warped surface may be considered as having been deformed in two manners; namely, by the change in area which has engendered tensional or compressional stresses or both and by bending which has occasioned stresses characteristic of cross-bending. For purposes of the present analysis it appears best to consider these two phases of deformation independently.

Changes in area due to warping.—If a sheet of rubber is held between two clamps, as in Figure 6, and subjected to torsion by turning one of the clamps (maintaining a constant distance between the clamps) the effect is to increase the area of the rubber

sheet. Plainly the center line of the rubber (the axis of torsion) remains unchanged in length, but the lateral margins are stretched, because the rotating of one clamp increases the distance between the ends of the two clamps. This stretching is maximum at the free edges of the rubber and decreases toward the center. The effect of tension thus developed is illustrated in Figure 7, which shows the cracks developed in the paraffin layer as a result of torsional warping of the rubber. Distribution of the cracks shows plainly

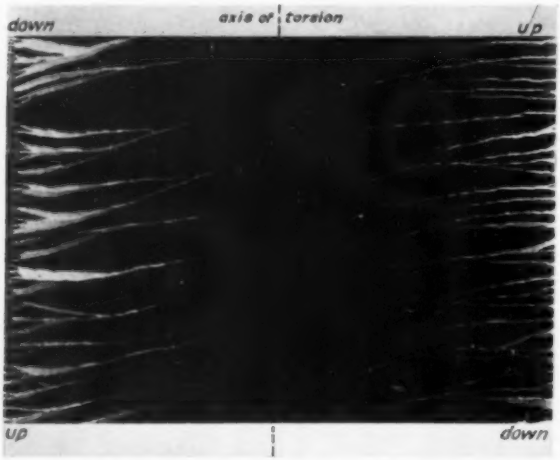

FIG. 7.—Fractures produced in paraffin coat on rubber sheet by torsional warping. (See Fig. 6 and 10C.)

the increase in the amount of tension as the margin is approached. The confluent nature of the cracks, resulting in a minimum number of free ends, is an interesting feature.

The rubber sheet may be so arranged that the free edges remain constant in length during torsion. If the rubber sheet thus mounted is subjected to torsion, there can be no change in the lateral margins. There is a change, however, along the center line because the turnable clamp approaches the other as it is turned, thus causing shortening or compression along the center line. This compression is maximum along the center line and decreases to zero at the edges. A paraffin coat on the rubber

sheet thus deformed develops characteristic overthrust faults of the type shown in Figure 3, which are most numerous along the center line and decrease in abundance and displacement toward the margin.

We have in these two types of deformation limiting cases, neither of which is probably realized under natural conditions. In the first case there is a net increase in area; in the second case a decrease in area. We may now consider an intermediate case in which the total area remains constant. This in terms of the

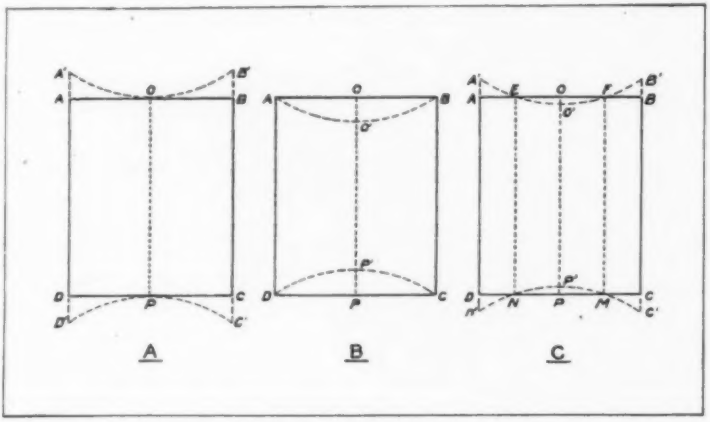

FIG. 8.—Illustrating changes in area due to torsional warping of a rectangular surface. In A the line *O–P* on the axis of torsion has remained constant in length resulting in a net increase in area from *ABCD* to *A'OB'C'PD'*. In B the lateral edges have remained constant in length and the result of warping is a decrease in area from *ABCD* to *AO'BCP'D*. In C the area has remained constant during warping resulting in elongation of the margins, shortening along the axis, and no change along the neutral lines *E–N* and *F–M*.

rubber sheet would result in tensional stresses along the free margins and compressional stresses along the center line with a neutral zone of neither compression nor tension on either side of the center. These three cases are illustrated in Figure 8. In each case the rectangular area represents the outline of an undeformed surface. The area with curved ends represents the surface

which has been deformed by warping and then flattened out for comparison with the original area.

Cross-bending stresses resulting from torsional warping.—We have so far considered only the stresses resulting from change in area, and now turn to a consideration of the stresses due to warping or cross-bending. In Figure 9 a warped surface is represented in isometric projection. In one set of diagonals the lines curve downward toward their centers forming a synclinal depression. In the other set of diagonals the lines curve upward toward their centers and form an anticlinal elevation.

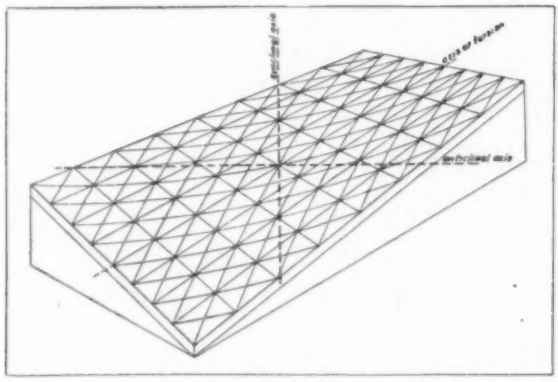

FIG. 9.—An isometric representation of a warped surface

If we consider a sheet of finite thickness to be thus deformed it is evident that on the upper surface compressional stresses will be developed at right angles to the axis of the synclinal depression and that tensional stresses will be developed at right angles to the axis of arching. At every point on the upper surface of this warped sheet there is a tensional stress and a compressional stress acting at right angles, each of them at an angle of 45° to the axis of torsion. On the lower surface it is evident that similar stress conditions exist but the tensional and compressional stresses are acting at angles of 90° to the similar stresses at the upper surface. These stresses are caused by cross-bending, and tensional conditions on one side mean compressional conditions on the opposite

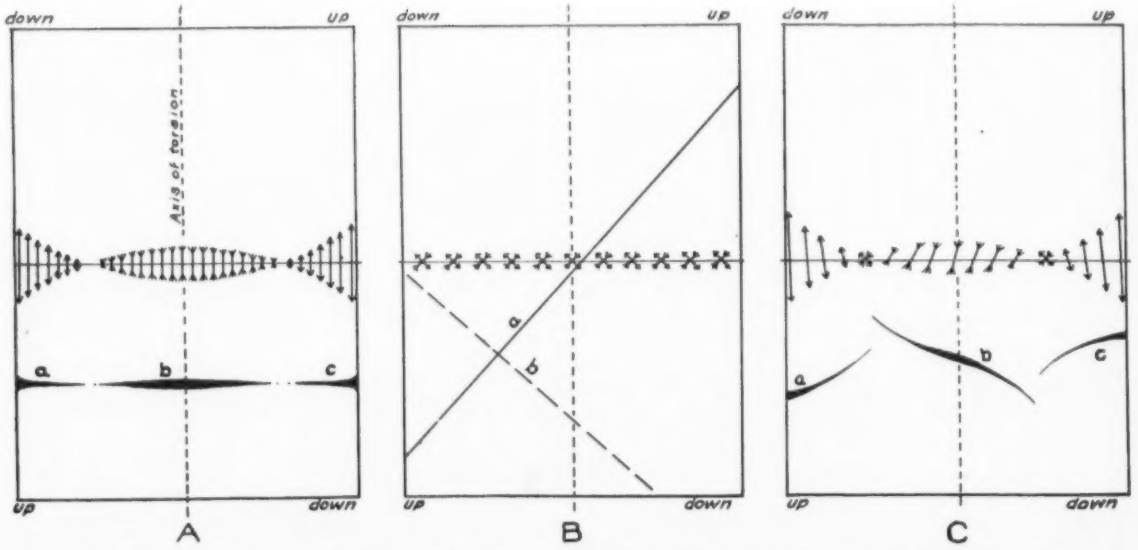

FIG. 10.—A. Stresses caused by local changes in area due to torsional warping, while the total area has remained constant. (See Fig. 8C.) Arrows indicate direction and relative magnitude of stresses *along any transverse line*. The heavy shaded lines indicate the direction and relative magnitude of resulting tension cracks at *a* and *c* and of compression fractures at *b*.

B. Stresses developed on the *upper surface* of a layer, due to bending caused by torsional warping. Arrows indicate direction and relative magnitude of stresses *along any transverse line*. The direction of tension cracks on the *upper surface* is indicated by the line *a*. The direction of tension cracks developed on the *lower surface* is indicated by the line *b*.

C. Resultants of stresses shown in A and B. Arrows indicate direction and relative magnitudes of resultant forces *along any transverse line*. The resulting type of tension cracks is shown by the shaded lines *a* and *c*. The shaded line *b* indicates the position and magnitude of the compression phenomena.

side just as in the case of a simple beam under load, in which compression is developed on the concave side and tension on the convex side.

Resolution of stresses due to change in area and to cross-bending—The stress condition at any point is the resultant of all of the stresses acting at that point. To determine conditions at a given point on the surface of a warped sheet it is necessary, therefore, to resolve the stresses due to cross-bending and the stresses due to areal change. In Figure 10A the stresses due to change of area caused by torsional warping are indicated in direction and relative

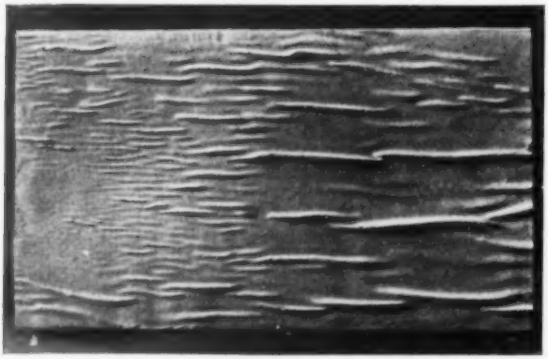

FIG. 11.—Plaster of Paris positive of folds produced by compression or shortening

magnitude by arrows. These represent the stresses occurring along *any transverse line of the warped sheet*. In Figure 10B the stresses due to cross-bending occurring along *any transverse line* of the warped sheet are shown by arrows in a similar fashion. In Figure 10C the resultants of the stresses in Figures 10A and 10B are shown. In Figure 10C typical cracks developed by tension and compression are shown at *a*, *b*, and *c*. The tension cracks *a* and *c* should begin at nearly 90° with the edge at the margin, and gradually curve to an angle of 45° at the neutral line. The curved line *b* indicates the strike of inclined thrust fractures which would be developed by compression. It is of interest to compare these curves with the tension cracks developed in paraffin on a rubber

sheet, illustrated in Figures 6 and 7. In this experiment constant distance between the clamps was maintained and compression along the center line thus prevented. The tension cracks are evidently due to a combination of cross-bending and stretching and are in accord with the conclusions indicated in Figure 10C.

Depending on the relative intensity of the stresses due to change in area and those due to cross-bending, the curvature of the cracks would vary from the position in Figure 10A, due only to change in area, to the position shown in Figure 10B, due only to cross-bending.

FIG. 12.—Vertical view of reproduction in plaster of Paris of folds produced by shearing deformation. The direction of movement is indicated by arrows and the amount of deformation is shown by the shape of the block.

Relative intensity of stresses due to cross-bending and those due to change in area.—With a given length of torsional axis the amount of cross-bending is a function of the angular displacement by torsion and is independent of the width of the warped sheet. The change in area (and therefore the tensional and compressional stresses), however, is a function of the width of the sheet as well as of the angle of torsion. It follows, therefore, that in narrow strips deformed by torsion, cross-bending stresses may be dominant while in wide areas a small angle of torsion with a small amount of resultant cross-bending may develop relatively large tensional and compressional stresses. Cross-bending stresses also increase with the thickness of the individual beds.

The classical experiment of Daubrée,[1] in which he twisted a narrow strip of glass and obtained systematic sets of fractures at approximately 45° with the axis of torsion, is familiar to most students of structural geology. The fractures thus developed in the glass are evidently due to cross-bending. The writer has repeated the Daubrée experiment and found that one set of fractures in the glass developed as tension-cross-bending cracks on one surface and that the other set of fractures at right angles to the first developed as tension-cross-bending fractures on the opposite surface. Therefore, a brittle rock formation broken in the manner illustrated by the Daubrée experiment would show a conspicuous set of tension cracks at 45° to the axis of warping and the other set would not be apparent, as it would be developed from the underside of the deformed rock stratum. In other words, if we look for a repetition of the Daubrée experiment in the field we should look for only one set of parallel tension cracks.

Use of the apparatus in the study of folds.—Previous experimentation in the reproduction of the structures of folded rocks in the laboratory has, so far as the writer is aware, been by means of the type of apparatus employed by Willis.[2] This type of apparatus with various modifications has been used by Hall, Lohest, Favre, Daubrée, Cadell, and others. In his investigation of the mechanics of Appalachian structure Willis used an apparatus of the piston or plunger type in which a series of wax layers of varying consistency were built up to resemble in their relative competence the rocks occurring in the Appalachian region. A load of shot was superposed to simulate the weight of overlying sediments and deformation was accomplished by forcing a piston or plunger against the end of the aggregate by means of a screw. Willis found that with flat-laying layers single folds were developed near the plunger and that repeated folds could be developed only when certain portions of the beds had an initial dip or when the first fold next to the plunger piled up material to such thickness and strength as to develop, as it were, an extension of the plunger which in turn caused a secondary fold in front of it.

[1] G. A. Daubrée, *Études Synthetiques de Géologie Expérimentale*, pp. 507–15.

[2] Bailey Willis, "Mechanics of Appalachian Structure, *Thirteenth Ann. Rept. U.S. Geol. Survey*, Part 2 (1893), pp. 241–53.

The apparatus of Willis permits deformation only by straight shortening or compression and does not afford means of studying the nature of folds developed by lateral shearing movements. It seems probable that the movements between great earth masses are in the nature of shears rather than simple straight-line compression. In other words, *the application of a compressive force directly toward the point of maximum resistance would be less probable than the development of a couple which would cause what has been called a rotational stress.*

It does not appear to the writer that rocks have been folded by forces transmitted to them in a manner at all similar to the action of a piston against a more or less confined mass but that shortening of the earth's crust has resulted from great compressive forces extending to some depth, and that the fracture and folded rocks within the zone of our observation have received from the rocks beneath, in a large measure, the force which deformed them. In other words, most of the faults or folds are the result of the riding or dragging of the upper layers by the underlying materials.

The writer has attempted to apply to the study of folds the methods used in the study of fractures already described. The two pieces of apparatus shown in Figures 1 and 4 were employed but instead of the thin brittle coat of paraffin a very thin layer of plastic wax (made by mixing beeswax and Venice turpentine) was applied and over this, while the wax was still sticky, a sheet of tinfoil was carefully spread. When the rubber sheet was allowed to shorten, or was deformed by shear, the layer of wax and tinfoil developed a series of folds. It was found that a very thin sheet of rubber served the same purpose as the tinfoil. The purpose of the thin sheet of rubber or tinfoil is to supply a layer with a certain small amount of competency. A layer of wax alone is entirely incompetent and follows the deformation of the rubber sheet without development of folds. A thin layer of tinfoil, sheet rubber, or waxed paper supplies the element of competency which results in the development of folds.

Folds developed by pure shortening or compression.—The apparatus shown in Figure 2 was employed, with a layer of plastic wax covered by a sheet of thin dental rubber. The shortening was

produced by allowing the thick rubber sheet to contract. This resulted in the development of the system of folds illustrated in Figure 11. This figure represents a positive reproduction of the surface of the specimen in plaster of Paris. The original specimen was not of a nature to be easily photographed. This experiment and others of the same type show a set of folds striking in a direction at right angles to the direction of shortening. All of these folds pitch at the ends and disappear. Depending on the thickness of the wax and the behavior of the rubber sheet, shortening is accomplished by a few large folds or by a larger number of smaller folds. An interesting overlapping of the folds is noted. Whenever a fold terminates by pitching, another fold appears overlapping it and continuing the necessary amount of shortening. The experiments demonstrate very well that pitching folds do not necessarily mean cross-folding but that they are developed in flat-lying beds with perfectly even application of shortening stresses.

Development of folds under conditions of shear or rotational stress.—The apparatus used is illustrated in Figure 4, except that in place of a thin layer of paraffin, a very thin layer of plastic wax was applied to the very tightly stretched rubber sheet and over this a sheet of tinfoil was carefully spread, care being taken to secure perfect adhesion of the tinfoil to the underlying wax. Deformation was accomplished by causing the slidable clamp to move parallel to the other clamp by means of the screw. This resulted in a set of folds in the tinfoil-covered wax layer, shown in Figure 12. The illustration is from a photograph of a positive reproduction of the specimen in plaster of Paris. The direction of shearing forces is shown by the arrows and the amount of deformation by the shape of the parallelogram which was originally rectangular. The folds, it will be noted, have their axes parallel to the direction of elongation of the mass. All of them are pitching folds. They illustrate the phenomenon of repeated folds. Like the previously described experiment they demonstrate that pitching folds do not necessarily mean cross-folding or shortening in the direction of the axes. As a matter of fact, in this experiment tensional stresses existed in the direction of the axes of the

folds and actual open ruptures in the tinfoil occurred across some of the folds but were not preserved in the process of casting.

A rather striking similarity between the folds illustrated in Figure 9 and the structure of the southern Appalachians is apparent and the writer ventures to suggest that perhaps certain of the characteristics of the southern Appalachian structure, such as repeated folds, pitching folds, and repeated thrust faults, may receive a certain amount of new light by viewing them with the conditions of the above-described experiment in mind. Whether the deformation was accomplished by straight compression between the oceanic segment and the continental mass or by a shearing movement between these great segments cannot be said. It seems, however, that the latter is rather more probable mechanically and that the foregoing experiment demonstrates that the folds of the Appalachians could have been produced by such shearing movement.

PRELIMINARY DESCRIPTION OF A NEW SUBORDER OF PHYTOSAURIAN REPTILES WITH A DESCRIPTION OF A NEW SPECIES OF *PHYTOSAURUS*

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The Triassic beds exposed in a narrow strip along the eastern edge of the Staked Plains in western Texas have not been intensively studied and are now grouped together under the name given by Drake, the Dockum beds. Drake recognized an indefinite tripartite division of the beds which may later be distinguished as recognizable horizons. The vertebrate remains which have so far been recovered from these exposures are all members of the reptilian order Parasuchia and of the stereospondylus stegocephalia and are indicative of an upper Triassic age. Summary accounts of the reptilian forms previously described have been given by McGregor and Mehl.[1]

In the year 1917 the author, while on a hurried trip across the plains, found near the now little used crossing of the Blanco or Catfish River on the road from Spur, in Dickens County to Crosbytown, in Crosby County, a series of vertebrae, with portions of the dorsal armor, of a reptile which appeared to be of the usual phytosaurian type and were referred, in the museum catalogue, to *Phytosaurus buceros* Cope with question. In 1919 a chance was afforded to revisit the locality and considerably more of the same specimen was recovered. The material now in hand includes most of the vertebral column with exception of the posterior part of the tail, much of the dorsal armor and the skull, lacking the anterior end of the nose and the lower jaws. The skeleton was found in a sandy clay mixed with abundant fragments of vegetation and the bones were coated with a tough layer of gypsum which has in places penetrated and rotted the bones and in other places left

[1] J. H. McGregor, *Mem. Am. Mus. Nat. Hist.*, Vol. IX, Part XI, 1906; M. G. Mehl, *Jour. Geol.*, Vol. XXIII (1915), p. 129.

them in singularly good condition. The bones were disturbed when deposited so that only a few of the cervical and of the dorsal vertebrae were found in series. That the bones are those of a single individual is indicated by the fact that they were found in a single mass and that no other bones were found, even after a careful search, within a half-mile of the small patch where they were found, but that there is some room for doubt is indicated by

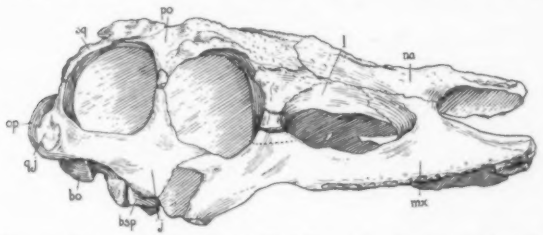

FIG. 1.—Lateral view of the skull of *Desmatosuchus spurensis*, $\times\frac{1}{4}$

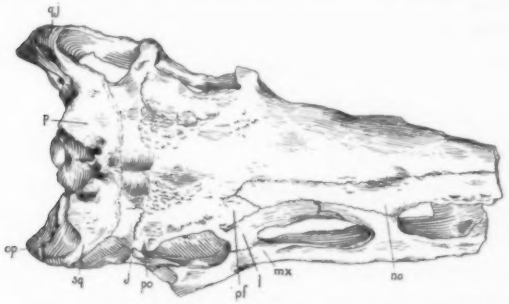

FIG. 2.—Upper view of the skull of *Desmatosuchus spurensis*, $\times\frac{1}{4}$

the fact that it seems impossible to fit two of the isolated cervicals into the series and that there are more dorsals than are usually found in the Parasuchia. These points are significant because the skull and the dorsal armor are so radically different from any form yet found while the vertebrae are typically Parasuchian. If, though it seems impossible at present, the remains are finally shown to belong to more than one individual, the skull must remain the type of the new sub-order and the vertebrae and dorsal armor must be described separately as a new form.

The character of the skull is shown in Figures 1, 2, and 3. It is astonishingly small for the size indicated by the vertebral column. The basi-cranial region is distinctly phytosaurian in size and the arrangement of the elements but the skull as a whole shows several marked peculiarities. There is a single large lateral temporal fenestra with no trace of an incipient or disappearing upper fenestra. The quadrate is so far reduced that it occupies a depression bounded by the opisthotic and the quadrato-jugal (?); the large, laterally directed orbits are preceded by large, elongate antorbital vacuities and these by smaller, elongate narial openings which lie entirely on the side of the nose; the teeth are small (as indicated by the sockets and a single poorly preserved tooth), are of equal size throughout the length of the maxillary, and were set in deep sockets; the posterior surface of the skull is completely closed except for the large foramen magnum and two small openings, amounting only to foramina, which occupy the position of the posterior temporal openings.

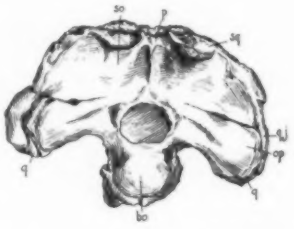

FIG. 3.—Posterior view of the skull of *Desmatosuchus spurensis*, $\times\frac{1}{4}$

The anterior end of the skull is missing but there is every indication that the nose was short. The close anchylosis of the bones and the coarse sculpture of the upper surface of the skull prevents the determination of many of the sutures; such as have been located are indicated upon the figures. As it has been shown by v. Huene and others that *Aëtosaurus* possessed upper temporal openings and as such openings are present in the Proterosuchia, their absence in the form here described is alone sufficient to indicate its isolated position.

The vertebral column so closely approaches that of the Parasuchia that it need not be discussed in a preliminary description.

The dorsal armor consists of four rows of plates, two on each side of the median line. The rows are made up of incomplete rings covering the dorsal portion of the body. Whether there was any armor on the sides or the abdomen is uncertain; a single

small plate of irregular form such as occurs on the lower part of the body of the Parasuchia was found with the specimen but its position is uncertain.

The dorsal armor is most conveniently described as a series of transverse arches. The first five are not metamerically arranged with relation to the vertebrae; they cover the first ten vertebrae, rather more than the whole cervical series; posterior to this the plates correspond in number and position with the vertebral segments below. Each arch consists of a pair of median plates with a low blunt spine or knob, and a pair of outer plates which carry spines of varying size and form. The plates of the first five arches have only a slight sculpture, those posterior to the fifth have an increasingly heavy sculpture of pits and ridges which soon becomes very coarse. The form of the various plates is shown in Figure 4, which is a semi-diagrammatic restoration of the dorsal armor. Except for the three posterior dorsal arches and the median caudals there is evidence for all the parts. The arrangement of the plates is such as is dictated by the form and characters of the units, none having been found in sequence posterior to the cervical region.

The first five arches show a gradual increase in the size of median plates and a rapid increase in the size of the spines upon the lateral plates. In the fourth arch the median and lateral plates of the right side are co-ossified and in the fifth arch the median plates of both sides and the lateral plate of the left side fit well together; in these arches there can be no doubt of the position and direction of the spines and by analogy with these the position of the other plates and spines is determinable. The fifth arch is most astonishing in the development of the relatively enormous spines which extend outward almost horizontally and curve forward over the third and fourth arches. In all of the arches of the cervical region the plates are thickened at the point of juncture in the same arch and thinned anteriorly and posteriorly to permit of the overlapping from before backward and allow for slight vertical movement of the head and neck; any lateral movement, as indicated by the form of the plates and the faces of the vertebral centra, must have been very slight.

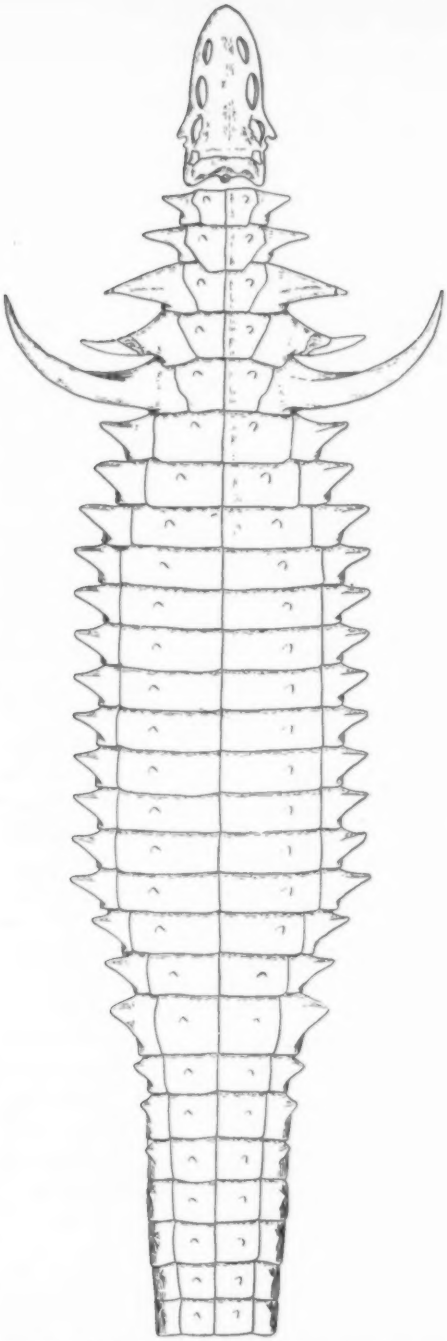

FIG. 4.—Restoration of the dorsal armor of *Desmatosuchus spurensis*, $\times \frac{1}{24}$

Posterior to the fifth arch the median plates become shorter antero-posteriorly and elongate laterally to accommodate the broadening of the back. The lateral plates have a distinctly angular form, the inner half of the base shorter and nearly horizontal, the outer half longer and extending outward and downward at a slight angle. The spines are directed outward and slightly forward. In the pelvic region is placed a broader arch followed by a narrower one; this arrangement is only tentative, but the plates can hardly go elsewhere and it has been pointed out to the author by Professor Alexander Ruthven that such an arrangement of scales and scutes is not uncommon in living forms. Only the anterior portion of the tail is represented and only by plates of the lateral series. It is altogether probable that the median plates gradually disappeared as in the living Crocodilia. The lateral plates have well-developed spines and the outer half of the base is elongated and extends downward almost directly in the same plane as the outer side of the spine, indicating that the sides of the tail were elevated and flattened, not rounded. The length of the tail is uncertain.

The exact position of this peculiar form is undeterminable as yet; its phytosaurian affinities are beyond question, but whether it is to be regarded as a highly specialized form of a more primitive type retaining characters of the primitive single-arched reptiles and placed near the origin of the Parasuchia, or a specialization of a more advanced type, remains to be determined after more complete preparation and the assemblage of the material in a mount. An attempt to obtain more material is in progress.

For this new form, indicating the skull as the characteristic portion of the holotype, I would suggest the name *Desmatosuchus spurensis*, with the family and sub-order *Desmatosuchidae* and *Desmatosuchia*.

ON A NEW SPECIES OF PHYTOSAUR FROM THE DOCKUM TRIASSIC BEDS OF TEXAS

While on a trip through a portion of the Triassic beds of Texas in the summer of 1919 the author was privileged to examine the collection of Mr. George D. Doughty, of Post City, Texas. In this

collection is the posterior portion of the skull of a large Phytosaur preserved in a soft yellow clay. The bones are somewhat rotted and broken but, as is common in specimens preserved in such a matrix, the sculpture and the sutures are exquisitely preserved. Mr. Doughty was so kind as to loan this specimen to the author for study and illustration. As preserved and collected, the posterior part of the top of the skull and the left side are present as far forward as the nares and the posterior end of the antorbital opening. The lower part of the skull is lost and the occipital region is represented by a detached fragment. The skull was distorted in fossilization so that the left temporal region is pushed outward at a decided angle. Figures 5 and 6 show the sculpture of the bones and the position of the sutures so clearly that extended description is unnecessary.

The lateral temporal opening is rhomboidal in outline with the long axis inclined obliquely forward and back. Its upper border is formed by the squamosal and postorbital. The squamosal is fairly flat on the upper surface and marked with a low relief of broad rugosities. The descending process on the outer side is smooth and widens toward its connection with the quadrato-jugal. The posterior end is widened and the inferior face is marked by two shallow, elongate, depressions, probably the location of cartilaginous attachment to the opisthotic. Just anterior to these there is a deep pit which received the head of the quadrate. There is a total lack of any descending, hooklike process posterior to the quadrate and defining the otic notch.

The parietals are flat or slightly concave; the posterior ends are broken off but there is clear evidence that the posterior ends were below the level of the squamosals and that there was no elevated arcade defining the posterior border of the upper temporal opening.

The quadrate was erect and its greatest breadth lay almost at right angles to the squamosal and the quadrato-jugal. Its anterior face is sharply concave, the inner border extends more forward than the outer and is very thin; apparently only the lower part of this inner edge united with the pterygoid.

The quadrato-jugal is peculiar in its mode of articulation with the jugal and the squamosal; the anterior and upper edges are

split and the lower edge of the squamosal and the posterior edge of the jugal are deeply dovetailed into the quadrato-jugal. This relation is clearly shown by the distinct and perfectly preserved sutures. From this peculiar relation it follows that the quadrato-jugal occupies very nearly as large an area on the inner side of the

FIG. 5.—Upper view of the skull of *Phytosaurus doughtyi*, $\times\frac{1}{4}$

temporal arch as on the outer, though it forms but a small portion of the posterior lower edge of the temporal opening. The attachment of the quadrato-jugal to the quadrate is by a broad, flat suture, interrupted by a good-sized quadrate foramen.

The jugal extends forward in a nearly straight line, not rising sharply or even bending upward to form a notch below the lateral temporal opening. It is not certain, but possible, that an anterior

extension of the jugal took part in the posterior edge of the ant-orbital opening. On the inner side of the anterior lower angle of the jugal are two articular faces which are separated by a deep groove; this when opposed to the maxillary would form a large foramen.

Fig. 6.—Lower view of the skull of *Phytosaurus doughtyi*, ×½

The orbits are nearly circular and are separated from the lateral temporal opening and the antorbital opening by strong bars. The anterior bar, formed by the lachrymal, is without sculpture but there is no indication of the opening extending backward in a depression on the surface of this bone.

The nasals are nearly flat in their posterior part but rise sharply to the posterior edge of the nares, which open upon a considerable

elevation. The nasals are short, not extending, apparently, anterior to the openings, and they do not separate the nares. The septum is formed by thin, paired plates which rise from below, as in most of the Phytosaurs; these are apparently the mesethmoids. The surface of the nasals, together with the surface of the frontals and parietals, are deeply sculptured. The nasal canals extend sharply backward as well as downward.

On the under side of the specimen the walls of the brain case are broken and lost from a line above the otic region. The bones which form the remnant of the brain case extend forward in sharp processes which lie in grooves on the lower surface of the frontals; these are probably the alisspenoids. The channel for the forward extension of the olfactory portion of the brain is well defined. At the point of junction of the postorbital, postfrontal, and parietal there are deep pits, transversely elongate, on either side. The function of these is obscure; they are perhaps connected with the orbitopineal process of the brain described by Cope in the cast of the brain cavity of *Phytosaurus buceros*.[1]

MEASUREMENTS	MM.
Posterior edge of nares to posterior end of squamosal	406.8
Top of squamosal to base of quadrate	233.6
Width across lower face of quadrate	83
Interorbital space, narrowest	62
Center of foramen magnum to end of opisthotic	124.7

A consideration of this brief description and the accompanying figures will show that this specimen differs at least specifically, from any yet described, and the name *Phytosaurus* (*Machaeroprosopus*) *doughtyi* is proposed for it in honor of the discoverer.

From the published figures of *Phytosaurus kapffi* given by v. Huene[2] this specimen differs notably. The quadrate fits into a pit on the lower side of the squamosal and is supported above by the opisthotic and below by the pterygoid; the latter is attached to the lower half of the quadrate and does not appear on the posterior lateral face of the quadrate as suggested in Huene's Figure 15.

[1] *American Naturalist*, Vol. XXII, p. 914.

[2] *Geol. u. Paleontolog. Abhdlg.*, N.F., Bd. X, 1891, Figs. 14–16.

The opisthotic and pterygoid join the quadrate by separate attachments in a manner quite different from that suggested by Huene, Figure 16. From this and all other described Phytosaurs it differs in the absence of a descending hook from the squamosal posterior to the quadrate, outlining the otic notch.

From *Paleorhinus*[1] it differs in the more posterior position of the nares, these lying over the antorbital opening as in the Phytosaurus type rather than anterior to it as in the Mystriosuchus type. The nasals are shorter and do not separate the nares nor extend anterior to them. No otic foramen is present. The quadrate foramen is entirely on the posterior face of the skull. The pre-frontal is much shorter and lies almost entirely anterior to the frontal. The lachrymal is stouter and forms a broad bar between the orbit and the antorbital opening. There is no evidence of a depression extending to the lachrymal from the posterior edge of the antorbital foramen and the lachrymal had little or no connection with the maxillary. The lower edge of the lateral temporal opening is convex upward, not concave.

From *Angistorhinus* it differs in the quadrangular rather than the oval form of the lateral temporal opening; in having the parietal-squamosal arcade depressed; in that the orbits are rounded instead of oval; in the position of the orbits which are more anterior in reference to the lateral temporal opening; in that the parietals meet anteriorly in a recess rather than in a point; and in that the opisthotic is more spatulate at the outer end.

From *Machaeroprosopus* it differs in the greater distance between the center of the orbit and the posterior end of the nares, 74 mm. instead of 40 mm. The nasals do not include nor extend in front of the nares. The frontals are longer and narrower; the jugals probably take little part in the posterior edge of the antorbital foramen. The quadrate foramen is small. The pterygoid is absent but it does not appear that there could have been any extension in the form of a wedge or hook between the quadrate and quadratojugal, as described and figured by Mehl.

[1] Bibliographies of the American Triassic Phytosaurs are given by McGregor, *Mem. Am. Mus. Nat. Hist.*, Vol. IX (1906), Part XI; and Mehl, *Jour. Geol.*, Vol. XXIII, No. 2, 1915.

From *Phytosaurus buceros* it differs in the more rounded and shorter posterior process of the squamosal. The lateral temporal opening is larger and more quadrangular in outline. The antorbital opening was more rounded at the posterior end. The jugal passes forward in a nearly straight line, not bending sharply upward, to form a notch in the lower border of the temporal opening.

Mehl in his account of the skull of *Machaeroprosopus*[1] has indicated his belief that the form described by him is congeneric with Cope's *Phytosaurus buceros;* but because he agreed with Jaekel that Cope's form is a distinct genus and because Jaekel's name, *Metarhinus*, is preoccupied, he suggested the new name *Machaeroprosopus*. It is far from certain that the European type of Phytosaurus does not occur in North America; Huene has rejected Jaekel's distinction between *Phytosaurus buceros* and the European forms, and to the author it seems very doubtful on present evidence that such a distinction is justified. For this reason he prefers to refer the new species to the genus *Phytosaurs* (*Machaeroprosopus?*) with Cope's *buceros* and Mehl's *validus* and *gracilis*.

[1] *Quart. Bull. Univ. Oklahoma*, N.S., 103 (1916), p. 21.

THE HEART[1] MOUNTAIN OVERTHRUST, WYOMING[2]

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SUMMARY OF RESULTS

The recognition in 1919 of blocks of Madison limestone (Mississippian) overlying beds of the Bridger epoch (middle Eocene) in the McCullock Peak region, 12 miles east of Cody, Wyoming, shows that the overthrust fault recognized by Dake (2) in 1916 is much more extensive than first suspected. Dake mapped the fault in a belt 30 miles long, within which the extent of overthrust was estimated at 16 miles. He also noted the existence of thrust faults along the east front of Beartooth plateau, where pre-Cambrian rocks overlie "Red Beds" (Chugwater formation) but did not assume continuity with the Heart Mountain overthrust. The residuals on McCullock Peak show that the extent of overthrust is at least 28 miles and indicate that the fault should be traceable

[1] This spelling approved by United States Geographic Board, 1909.

[2] Published by permission of the director, United States Geological Survey.

over the entire eastern edge of Absaroka Range, perhaps for 125 or 150 miles.

On the basis of exposures in the mountain region, Dake was able to conclude that the overthrust took place after the deposition of his Fort Union (?) (early Eocene) beds and before the outbursts of the "early basic breccias (Neocene or upper Miocene)" described by Hague. The McCullock Peak outliers show that the overthrust is probably post-Bridger (middle Eocene).

It may be recalled that Richards and Mansfield (15*a*) concluded that the Bannock overthrust in southeastern Idaho was developed before the deposition of Wasatch beds (lower Eocene). Similarly Veatch (16*a*) concluded that the Absaroka overthrust in southwestern Wyoming was developed after the deposition of the Almy and Fowkes beds (lower Wasatch) and before the deposition of the Knight formation (upper Wasatch, lower Eocene). On the north, Willis (17*a*) concluded from physiographic rather than stratigraphic evidence that the Lewis overthrust was developed in mid-Tertiary time, and was completed before the Miocene epoch. Although further work will undoubtedly determine more closely the periods at which these four overthrusts were developed, it appears highly probable at present that, although they lie in a belt scarcely 500 miles long, they did not take place simultaneously. The Lewis overthrust may have been nearly simultaneous with the Heart Mountain overthrust, however.

A brief reconnaissance by the writer in the region west of Cody studied by Dake confirmed his conclusion that the overthrust beds were deeply eroded before the outbursts of the early basic breccias of the Yellowstone Park region (upper Miocene). Evidence obtained by the writer previously between Owl Creek and Wood River, however, indicates that there was conformable deposition of the Bighorn Basin Wasatch and the overlying tuffs and breccias of that region, which are here tentatively correlated with the "early acid breccias" of the Absaroka Range (lower Eocene). It is conciuded that the overthrust took place after the deposition of the "early acid breccias" and before the outbursts of "early basic breccias" and is, therefore, middle Eocene or early Oligocene in age.

INTRODUCTION

It is the principal purpose of the present article to set forth observations in the McCullock Peak region that bear upon the extent and age of the Heart Mountain overthrust. It will be apparent, however, that such a profound structural feature must consistently fit into the complex Tertiary history of sedimentation and orogenic movements in the region, so that it seems advisable to set forth here some of the problems of the region and some of the data that must be adjusted to a correct and comprehensive interpretation of that history. As the writer has devoted parts of the field seasons of 1911, 1912, 1913, 1916, and 1919 to detailed investigations in three fifteen-minute quadrangles that lie between Cody and Thermopolis, southeast of the region in which the overthrust has been observed, some conclusions must be stated without giving much of the evidence on which they are based.

SURFACE FEATURES

The Bighorn Basin (4, 5, 14) is an elliptical area of low relief with few conspicuous hills or mountains, surrounded on the east, south, and west by mountain ranges. For purposes of physiographic, stratigraphic, and structural description, it may be considered as made up of two parts, a central part 75 miles long by 45 miles wide, which largely coincides with the area of Wasatch and younger beds, and a border belt 10 to 20 miles wide, which lies between the central part and the mountain ranges that surround the basin. These ranges include the Bighorn Mountains on the east, the Bridger and Owl Creek ranges on the south, and the Absaroka Range and Bear-tooth Plateau on the west. Figure 1 shows some of the features and geology of an area in the northwestern part of Bighorn Basin, which extend from the eastern edge of the Absaroka Range, across the border belt to the center of the basin. Figure 2 shows two sections across this region.

The central part of the basin contains large areas of flat uplands that lie several hundred feet above the nearby valleys. There are also extensive areas of bad lands where erosion has cut back into the uplands. The central part contains three conspicuous elevated areas that rise above the uplands, and that range from 1,200 to

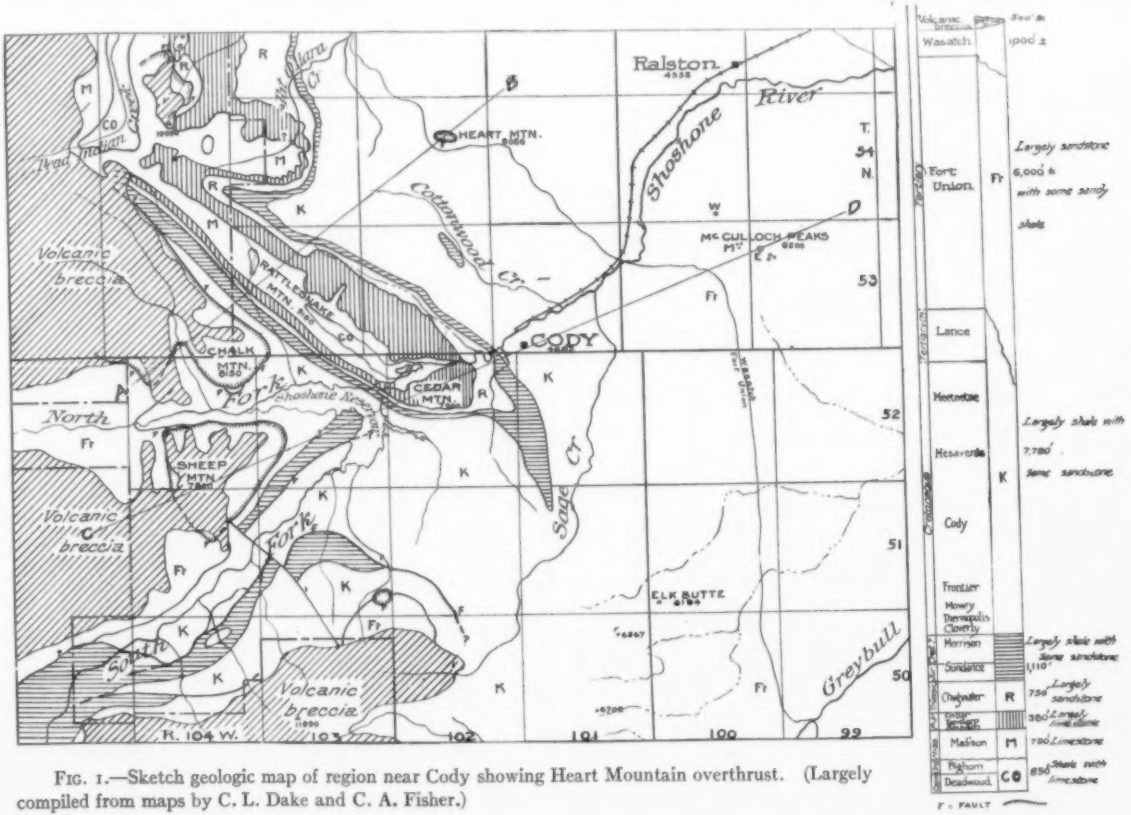

FIG. 1.—Sketch geologic map of region near Cody showing Heart Mountain overthrust. (Largely compiled from maps by C. L. Dake and C. A. Fisher.)

1,500 feet above the nearby streams; Squaw Buttes (6,200 feet), Tatman Mountain (5,800 feet), and McCullock Peaks,[1] three in number and approximately equal in elevation (6,200 feet). Heart Mountain (8,080 feet) is a conspicuous peak that lies west of the central part of the basin, where it merges with the border belt.

The border belt is largely made up of long stretches of flat upland terraces that rise gently toward the mountains. Most of the streams have cut broad terraced valleys below the uplands. The rocks exposed in this belt range from the Chugwater formation ("Red Beds") to the Fort Union formation (lower Eocene), and attain a maximum thickness of about 15,000 feet on the west side of the basin. The successive formations are brought to the surface in a series of pronounced folds whose axes are roughly parallel to a median trough in the central part of the basin. Dips that range from 15° to 60° are common along the flanks of the folds (14*a*).

In a broad way, the mountains that limit the basin on the east, southeast, and south, the Bighorn (4), Bridger (4), and Owl Creek (3) ranges respectively, are rather simple smooth ridges that coincide with extensive anticlines. The mountains west of the basin (10) are high and rugged and present an imposing front toward the basin. They coincide roughly with an area of volcanic tuffs, breccias, and flows that are a part of the extensive field of volcanic rocks which covers northwestern Wyoming and eastern Idaho.

STRATIGRAPHY

It will be sufficient at this place to state briefly the general features of the Paleozoic and Mesozoic sections and such details of the Fort Union, Wasatch, and younger rocks as bear upon the age of the overthrust and the physical conditions surrounding the process. The commonest underlying pre-Cambrian rock in this region is a rather homogeneous red granite which is locally cut by diabase dikes.

The Paleozoic and Mesozoic sections are separable into three groups on the basis of lithology and degree of induration, which measure their strength. The first and strongest group includes the Paleozoic limestones and associated sandstones and quartzites,

[1] Commonly referred to as McCullock Peak.

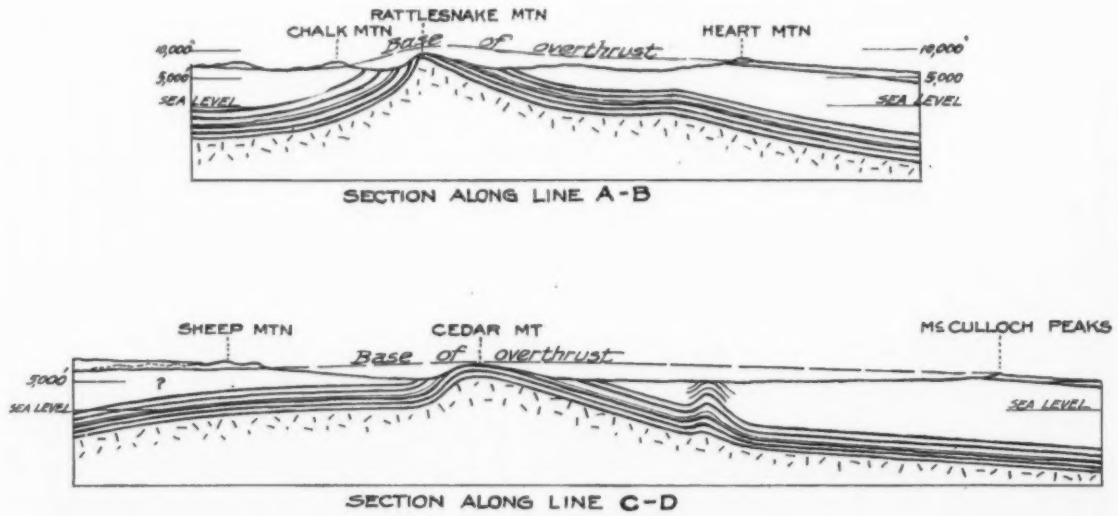

FIG. 2.—Cross-sections of the Heart Mountain overthrust

that include the beds from the Bighorn limestone (Ordovician) to the Embar group (Permian and Pennsylvanian), the sum of whose average thicknesses in this region is about 1,280 feet. Most of this thickness is beds of dense homogeneous gray limestone that range from 5 to 50 feet thick. This group is to be regarded as the most competent unit in the entire section.

The second group includes several distinct sandstone formations, such as the Chugwater (Triassic) about 750 feet thick, and Mesaverde formation (Upper Cretaceous), which is largely sandstone and about 1,200 feet thick. Both of these formations include some shale. As the Chugwater formation overlies the Paleozoic limestones and sandstones, it would tend to increase the strength of those beds.

The third and weakest group includes the remaining formations. The Deadwood formation (Cambrian) made up of shale and sandstone is 700 feet thick. The Mesozoic and Tertiary formations (12, 14) that are made up of thin soft sandstones, locally conglomerate, sandy shale, and shale include the Sundance, Morrison, Cloverly, Thermopolis, Mowry, Frontier, Cody, Meeteetse, Lance, Fort Union, and Wasatch formations, 13,600± feet thick.

It will be noted that the most competent unit is that which includes beds that range from the Bighorn limestone (Ordovician) to the Chugwater sandstones (Triassic) about 2,030 feet thick. If this section be compared with others of regions in which large overthrust faults have occurred, the thinness of the competent part of the section is impressive.

The characteristics and structural relations of those beds only that may bear upon the period of overthrusting will be presented here. The recognition of the Fort Union formation on the west side of Bighorn Basin is based upon numerous collections of leaves that have been studied and identified by F. H. Knowlton. The base is considered to be a conglomeratic sandstone, which is locally unconformable on underlying beds that range from the middle part of the Meeteetse formation (roughly equivalent to the Judith River formation of the Montana group) to the top of the Lance formation ("Ceratops beds"). This unconformity has only been recognized in one locality east of Oregon Basin for a distance of

15 miles where a maximum of about 2,000 feet of beds were here eroded before the deposition of the lowest Fort Union beds. The contact of these beds with the underlying Lance formation in a belt 50 miles southeast, however, yields no evidence of unconformity. The unconformity indicates local warping and erosion of the Lance and older beds before the deposition of the lowest Fort Union sandstone.

The top of the Fort Union formation in this region is a persistent unconformity at the base of beds that yield a large mammalian fauna until recently called Wasatch but now known to be characteristic of the Wind River formation (8, 9).

The unconformity is readily recognizable at every locality where dip cross-sections of the beds may be seen, but in strike sections it can only be detected by close study of the lithological features.

Within these limits, the Fort Union formation attains a maximum thickness of more than 5,250 feet and is made up of many beds of pale yellowish buff and white sandstone alternating with gray, olive, and red shale. The sandstones of the lower 200 feet commonly contain lenses of pebbles of many rock types. Black and gray chert predominate but red and gray quartzite, pale pink porphyry, gray sandstone, and silicified wood are common. Pink granite and coal pebbles are sparingly present but limestone has never been found. The chert pebbles have yielded an interesting collection of invertebrate fossils which are characteristic of the Madison and Embar formations. At least three coal beds occur in the lower 600 feet of the formation on the west side of the basin. Thus far, in this region, the formation has yielded a single vertebrate bone, but no invertebrate fossils. No bentonite or volcanic ash have been recognized in it.

There are good reasons for believing that the beds here considered as the Fort Union formation are part of an extensive sheet of sediments spread over a large area of Wyoming and Montana, at least as far west as the Rocky Mountains, and eastward into the Dakotas. They probably covered the site of the present Bighorn, Bridger, and Owl Creek Ranges. These beds are so involved in the folds of the border belt of the basin that it is concluded that these

as well as the long anticlines which coincide with the Bighorn, Bridger, and Owl Creek ranges, were developed after the beds were laid down. The folds are broken by many normal faults of small displacement, none of which appear to pass into the overlying Wasatch beds.

The term Bighorn Basin Wasatch has long been considered to include the sandstones and alternating olive and red clays of the central part of the Bighorn Basin, where they attain a maximum thickness of about 2,500 feet. These beds include light brown and white sandstones, gritty arkose and pale olive, gray, and red clays. The sandstones locally contain pebble zones of re-worked Fort Union materials, with the addition of limestone and granite which are absent or uncommon in those beds. Although bentonite has been reported east of Meeteetse (5), no unaltered volcanic tuff has yet been recognized. The beds are nearly horizontal over large areas in the center of the basin, and although the range along the border is commonly 3° to 10°, dips as high as 20° are known (9).

The beds of the central part yield a large vertebrate fauna which has been studied from time to time. Only a few invertebrate fossils are known in the beds (5). The recent careful faunal studies of Granger and Sinclair show that the Bighorn Basin Wasatch contains beds that range from "Paleocene" (their Clarks Fork beds) to uppermost lower Eocene (their Lysite or Upper Wind River beds) (7, 8, 9).

The early work of Eldridge (6) as well as the later work of Fisher (5) showed the presence of a persistent nearly horizontal layer, composed of sandstone and gray and red shale underlying volcanic tuffs in the region between Meeteetse Creek and Owl Creek in the southwest part of Bighorn Basin, and they were considered to be Wasatch. These beds outcrop along the south edge of the Meeteetse quadrangle and the west edge of the Grass Creek quadrangle which have been studied by the writer. In addition to the alternating olive and red shale and sandstones with local chert and quartzite pebble lenses, which are characteristic of the Wasatch deposits of the central part of the basin, there are thin beds of dark carbonaceous shale, carbonized plant remains, and

thin lenses of coal. The thickness of the layer ranges from 125 to 250 feet. It lies on a surface of low relief cut across the folded Cretaceous rocks, and as the base rises from an elevation of 6,000 feet near Owl Creek to 7,200 feet near Wood River, a distance of 21 miles, it appears to have been slightly warped since deposition. North of Cottonwood Creek a narrow east-west strip has been down-faulted about 360 feet.

Throughout this region, these beds are apparently conformably overlain by paper-thin carbonaceous shales that weather white, and these, in turn, by pale greenish volcanic ash and light brown tuff, locally indurated. About 100 feet above the typical Wasatch sediments, the well-stratified fine material is succeeded by coarser, cross-bedded light brown tuff and still higher by heterogeneous fine and coarse brown andesitic breccia that makes up the masses 3,000 to 4,000 feet thick in the region east of the Washakie Needles. Except for the reference to lava flows, which are not known between Wood River and Owl Creek, the following statement by Blackwelder might be considered an accurate description of conditions in the southwest part of Bighorn Basin (*1a*):

> At the northwest end of the Wind River Range, where it articulates with the mountains of Yellowstone Park, thick beds of volcanic ash and agglomerate with interbedded glassy lava flows rest upon the pre-Tertiary folded rocks, but are themselves younger than the Wind River Eocene. Traced eastward to Horse Creek, the Washakee Needles, and the valley of Owl Creek, this thick volcanic series is found to rest conformably upon the striped clays of the Wind River formation, with which they intergrade through gray, plant-bearing shales and greenish volcanic sandstones containing petrified logs. A closer examination of the volcanic beds shows that some of them are massive agglomerates, devoid of stratification, whereas other beds are distinctly stratified, cross-bedded, and occasionally interrupted by lenticular sheets of coarse gravel, suggestive of stream channels. The conditions indicated are those which would be found upon low gradient river plains adjacent to active volcanoes.

The stratified tuffs have yielded several collections of leaves, one collected by Mr. N. H. Darton (*3a*) on the Middle Fork of Owl Creek and one by the writer south of Sunshine. Both are considered characteristic Fort Union material by F. H. Knowlton. No vertebrate or invertebrate fossils have yet been found in the supposed Wasatch beds, or the overlying tuffs or breccias.

The relations between the beds described above, which may be referred to as the border Wasatch, to the Bighorn Basin Wasatch might be uncertain if it were not for the existence of remnants on hilltops in several parts of the border belt. These remnants have the same lithologic features as the border Wasatch and some of the beds rather high in the section of the Bighorn Basin Wasatch in the Tatman Mountain section. A longitudinal section through three of these remnants from a point south of Sunshine northeast toward the basin shows that they are part of a river channel which extended from the foothills of the border belt out into the basin with a gradient of 25 to 70 feet to the mile. It is the writer's opinion that the border Wasatch was laid down at the same time as some of the beds that make up the Lost Cabin or Tatman Mountain beds (upper Wind River) of Sinclair and Granger in the central part of Bighorn Basin. The particular significance of the border Wasatch beds is that they indicate that there has been little if any local folding of the Cretaceous and Fort Union beds of the border belt since upper Wind River beds were laid down. The border Wasatch has, however, been broadly warped and locally faulted.

Only tentative conclusions concerning the age and correlation of the stratified tuffs and breccias that overlie the border Wasatch can be made at this time. In considering this problem the writer has had the benefit of informal discussion with Dr. J. P. Iddings, who examined a large part of the area of the Yellowstone Park (11) and that covered by the Absaroka folio (10).

It may be recalled that along the headwaters of Lamar River (Cache Creek) and Clark's Fork (Republic Creek) several varieties of light colored andesitic tuffs and breccias, locally distinctly stratified, underlie the darker, basaltic breccias that cover a large area east of Yellowstone River and Lake, and north of the latitude of Greybull River (10). Although locally, the lower group ("early acid breccias") appears to merge upward with the upper group ("early basic breccias"), elsewhere there is evidence of considerable erosion of the lower group before the deposition of the upper group. The lower group yielded a large flora, considered by F. H. Knowlton to be Fort Union (lower Eocene), whereas the flora of the upper group, likewise large, is considered to be upper Miocene. From

the evidence of this region, one must conclude either (1) that the period of erosion intervening between the deposition of the two groups of breccias was brief and therefore that the floras are misleading, or (2) that the intervening period of erosion was rather long, probably persisting from upper Eocene time through Oligocene and lower Miocene time, as the floras indicate. Dr. Iddings agrees with the writer that the latter conclusion is more acceptable at present. He further considers that the lithology and flora of the tuffs and breccias between Owl Creek and Wind River warrant the tentative correlation of them with the "early acid breccias" of the Yellowstone Park region. It is apparent, however, that considerable additional work must be done before the relations of the volcanic rocks of the southern Absaroka Range are proved.

MCCULLOCK PEAK EXPOSURES

The foregoing statement of the lithologic features and structure of the Fort Union and Wasatch beds of the Basin permit a more careful consideration of the exposures near McCullock Peak and the relations of the overthrust recognized by Dake west of Cody.

In previous descriptions of this region, the name "McCullock Peak" has been applied to the central part of a high rugged area, about 4 miles long by 2 miles wide, 12 miles east of Cody. (Figure 3 shows a view of the McCullock Peak area from the west.) In the following description of the region, three culminating summits will be referred to as West Peak, Middle Peak, and East Peak, respectively. Although extensive gravel-covered terraces extend south from the peaks for several miles, the entire elevated region is completely surrounded by typical bad lands, and the rock exposures are uncommonly good.

West Peak lies about two miles northwest of Middle Peak and is connected with it by a sinuous rugged ridge. It is the culminating point of a rugged bad lands area carved from nearly horizontal Wasatch beds. It is almost devoid of vegetation and the terraced ridges of alternating gray, olive, and red shale and sandstone present an impressive picture from the east, north, and west. It was not visited by the writer, but several attempts to ascend it by horseback from the west are known to have failed.

Middle Peak may be readily ascended from the south along a gravel-covered terrace of gentle gradient. The summit is smooth and the adjacent slopes, except on the north and west, are covered with grass and dwarfed sage-brush. If viewed from the west, the summit appears to be a part of the terrace which extends southward, but if critically viewed from the south it appears to be a smooth hill that projects about 200 feet above the extension of

FIG. 3.—The McCullock Peak region viewed from the southwest, near Cody, Wyoming. West Peak lies on the left; East Peak rises above the terrace on the right; Middle Peak is the low cone just left of East Peak.

the terrace. In other words, it appears to be the residual mass of a more imposing hill that was in existence while the plain of which the terrace is a remnant was being formed. Good rock outcrops are confined to the west, north, and northeast slopes of Middle Peak, where nearly horizontal sandstones, locally arkosic, alternate with pale olive and red clays. The material is similar to that which makes up the bulk of the Bighorn Basin Wasatch. The

fossils which are described below were collected from a 50-foot zone of gray, olive, and red clays that are well exposed along a narrow ridge 1,000 feet northeast and 150 feet stratigraphically below the summit.

The fossils were first referred to J. W. Gidley of the United States National Museum, but, as field parties from the American Museum of Natural History have closely studied and made numerous collections from these beds, it seemed advisable to refer the fossils to them also. The statements of Mr. Gidley (*a*) and of Mr. Walter Granger (*b*) are attached:

a) A preliminary report was furnished to Dr. Stanton on November 25 (unofficially). It was as follows:

"No. 1. The largest tooth is a right upper third or last molar of *Helaletes;* cf. *nanus* Marsh. Not known outside the Bridger horizon.

"No. 2. The next smaller tooth is a last left upper molar of *Eohippus* sp.

"No. 3. The fragment of jaw containing two teeth I have not been able to definitely determine."

In addition, I may now say that a further study of the small jaw fragment seems to warrant referring it to *Hemiscodon pucillus* Marsh, with which it agrees almost exactly in size. This determination, however, cannot be made positive without comparing it with the type, which is probably in the Yale Museum collection. This is a Bridger species.

It would thus seem that the three specimens represent a Bridger fauna, although the Eohippus tooth suggests Wasatch rather than Bridger affinities.

b) I have examined the three specimens of mammal teeth from Eocene beds near the top of McCullock Peak, Wyoming, and submit the following determinations:

(1) *Helaletes*, a last upper molar of the right side.

(2) *Eohippus*, a last upper molar of the left side.

(3) *Tetonius* or *Absarokius*, a fragment of the right mandible, containing the first and second molars.

The Lophiodont genus *Helaletes* has hitherto been recorded only from the Bridger, but it might reasonably be expected from the uppermost levels of the Lower Eocene since another Bridger perissodactyl, *Hyrachyus*, has recently been found in the upper horizon of the Wind River (Lost Cabin beds).

The Hyracothere tooth shows characters most closely approached by the smaller specimens of *Eohippus* from the upper Wind River, as well as by specimens from the upper Huerfano, which is now regarded as the probable equivalent of the almost barren Bridger A.

The tiny jaw fragment of the Tarsiid cannot definitely be assigned to either of the genera mentioned because it lacks the diagnostic front teeth.

Tetonius, the type species of which is *Anaptomorphus homunculus* Cope, is recorded from the Gray Bull and Lysite horizons of the Bighorn and Wind River basins respectively, while the closely related *Absarokius* is from the Lysite and Lost Cabin horizons of the Wind River. The jaw appears to be of a new species, somewhat more progressive than any described form of either genus.

These three specimens seem to represent a fauna intermediate between that of the upper Wind River and that of Bridger B. It may belong to the base of the Bridger (Hor. A), the mammalian fauna of which is practically unknown, correlation with the upper Huerfano being made on a single specimen of Titanothere. In any event the McCullock Peak horizon is close to the border line between the Lower and Middle Eocene.

Dr. W. D. Matthew, who has also examined these teeth, concurs in the above identifications and in the conclusions regarding the age of the beds in which they were found.

Blocks, bowlders, and smaller fragments of dense cream to buff limestone are found on the summit of Middle Peak, as well as on the ridge that extends south and in the ravines cut below it. In an area on the summit about 600 feet square, there are no less than twenty blocks more than 3 feet in maximum dimension, and the largest is 5×5×10 feet. Most of the blocks are rudely rectangular and appear to be bounded by bedding planes and joints, although the surfaces are pitted and grooved by the solvent action of water. The blocks are irregularly distributed and there can be no doubt that they are not in place. The size, shape, and composition of the blocks as well as their distribution, are similar to those described by Granger and Sinclair (9*a*), to which a glacial origin was ascribed. Fossils collected from one of the blocks have been examined by Dr. George H. Girty, who reports that the following species are present: *Cliothyridina, crassicardinalis, Eumetria Verneuliana, Schuchertella aff. Chemungenis, Spirifer centronatus, Triplophyllum* sp. Dr. Girty states that this is a characteristic Madison fauna (Mississippian).

This collection may be compared with the following collection, also identified by Dr. Girty as belonging in the Madison limestone. It was obtained about 50 feet above the southwest base of the block of limestone that forms Chalk Mountain, west of Cody, where it overlies beds of Cretaceous age: *Triplophyllum excavatum, Schuchertella aff. Chemungensis, Camarotocchia metallica* (?),

Spiriferina soliderostris, *Cliothyridina crassicardinalis*, *Eumetria Verneuliana*, *Platyceras* sp.

South Peak lies about 8,000 feet southeast of Middle Peak and is formed by the conjunction of three smooth ridges that extend northwest, southwest, and east, respectively. The space between these two peaks is a smooth, rolling flat covered with sagebrush, and no rock outcrops were recognized in it. Just below the summit of this peak and well distributed around it there are six rugged outcrops of cream-colored limestone, each from 50 to 75 feet long. The limestone outcrops do not exhibit bedding but are highly shattered and several are entirely made up of angular fragments of limestone, one to ten inches in diameter, which are imbedded in a fine sand of similar material. The only fossils noted in these outcrops are a few crinoid stems, but the texture resembles that of the Madison limestone blocks on Middle Peak.

The best evidence of the character of the beds under the limestone is obtained at the head of a ravine on the northeast side of the peak, where the smooth surface near the summit merges with bad lands that show horizontal Wasatch material. No fossils were found at this locality. The evidence at South Peak indicates that a triangular cap of crushed Madison limestone, about 600 feet long and 400 feet across the base and about 80 feet thick, overlies horizontal Wasatch beds.

The summit of South Peak lies at the northwest end of an area about 3,000 feet in diameter within which there are eleven smaller and lower hills each of which shows outcrops of limestone breccia more than 50 feet long. Figure 4 shows one of the largest of these outcrops, in which the bedding is still preserved. It is 200 feet long, about 25 feet thick and, although it yielded no fossils, the texture indicates that it is probably part of the Bighorn limestone (Ordovician). Farther southeast these low hills merge with gravel-covered flat terraces that extend to the east and southeast toward the center of Bighorn Basin. Near the center of the hills, capped by limestone, there is a flat depression 500 feet in diameter at the northwest edge of which is Markham Spring, at an elevation of 5,850 feet. Even at the end of August, in the dry season of 1919, it yielded about two gallons a minute of clear non-alkaline water.

Another similar spring lies about 3,000 feet southwest at a lower elevation. These springs appear to be supplied from a thin mantle of mingled limestone breccia and sand from the Wasatch beds that becomes sufficiently saturated with water during the wet season to yield a small flow throughout the year. No other perennial springs are known within ten miles.

FIG. 4.—Bighorn limestone (?) overlying Wasatch (or Bridger?) beds on a hill near East Peak, McCullock Peak region, near Cody, Wyoming.

The significance of the McCullock Peak exposures may be briefly summarized. Before Dake's work was done in 1916, the McCullock Peak exposures might have been as puzzling as Heart Mountain to the geologists who examined that region some years ago (5, 6), and who considered that the block of Madison limestone which forms its summit was a plug bounded by a circular fault. In the light of Dake's work, there can be little doubt that the blocks of limestone in the vicinity of South Peak are parts of a layer of limestone that was thrust from the west, probably from the region

near Sheep Mountain between the north and south forks of Shoshone River, 28 miles west. It is impossible to imagine that the McCullock Peaks blocks are somehow related to another overthrust or to some obscure and complex structure, for the structure of the beds between the peaks and Sheep Mountain is completely shown in the canyon of Shoshone River (14).

The recognition of mammalian fossils characteristic of the Bridger formation of western Wyoming under the blocks of Madison limestone shows conclusively that the period of overthrust was no older than these beds.

PHYSICAL FEATURES OF THE OVERTHRUST

Sufficient information is not yet available to make a comprehensive statement concerning those features of the overthrust that are needed to interpret the conditions under which it developed. It may be that the thick masses of "early basic breccias" cover so much of the mountainward portion that a satisfactory explanation can never be given. The known exposures permit the following summary of its features:

1. The lithology of the beds and few fossils collected in the mountainward area indicate that the base of the overthrust is uniformly the base of the Madison limestone. Dake states that the base of the Heart Mountain block is Madison limestone. On the other hand, although the few bowlders on Middle Peak yield Madison fossils, the lithologic features of the East Peak remnants resemble the Bighorn limestone. The base of the overthrust is, therefore, probably not the same horizon throughout. A limestone breccia is present at the base of all of the blocks that were examined. In the few days available in the mountain region, the writer was unable to confirm Dake's conclusion that there are two surfaces of overthrust. Although the presence of Sundance fossils under the Chalk Mountain Block appears to be evidence that such is ithe case, the exposures along South Fork, where a lower surface s also mapped, do not appear to demand this interpretation.

2. The elevation of the base of the remnants of the overthrust block decreases from about 7,200 feet on Carter Mountain to, about 6,800 feet on Sheep Mountain, then increases to about

9,500 feet on the divide between Rattlesnake and Dead Indian Creeks. The base of the Heart Mountain remnant stands at about 7,200 feet and the McCullock Peak remnants from 6,100 to 6,200 feet. Rattlesnake Mountain, a persistent ridge which attains an elevation of 9,100 feet and lies between these two groups of remnants, was examined but does not appear to retain any remnants of the overthrust block, although it once overlay the mountain. It cannot be stated assuredly yet whether the differences in elevation here indicated represent the form of the original surface of overthrust or whether the surface has been subsequently warped. Although parts of the region have been warped since the deposition of the bedded tuff near Owl Creek, tentatively correlated with the "early acid breccias" (lower Eocene), the writer believes that a large part of the noted differences represent the form of the surface over which the block was thrust.

3. The structure and attitude of the remnants of the overthrust block indicate that it was a relatively simple, unfolded layer of rock. The thickness can only be conjectured. The entire Paleozoic, Mesozoic, and Fort Union sections above the Deadwood shale (Cambrian) are about 17,000 feet thick. In attempting to estimate the probable thickness of the block, it must be borne in mind that it was largely removed by erosion before the outburst of "early basic breccias" (upper Miocene). The writer would tentatively estimate the thickness near the mountains at 15,000 feet, but the eastern edge was probably much thinner.

4. The surface upon which the overthrust moved is cut across a sharply folded belt of rocks that range from the pre-Cambrian granite to beds that appear to represent horizon A of the Bridger formation. No part of this surface that has been studied appears to be a fracture across the beds, but it is probably a surface of erosion. To this extent it resembles Willis' interpretation of the Lewis overthrust (17).

5. Dake mapped the overthrust in an area thirty miles long and the McCullock Peak exposures indicate a minimum thrust of twenty-eight miles. Only casual consideration of the regional geology is needed to convince one that the overthrust must have involved a much larger area, over which it can probably be traced.

6. The relations of the border Wasatch and the residuals east of Sunshine indicate that the border belt of folds had assumed their present form and were truncated by erosion before these beds were laid down. Apparently, therefore, the folds were developed considerably earlier than the overthrust.

AGE OF THE OVERTHRUST

As a result of his work Dake concluded that the overthrust was younger than certain beds along the north and south fork of Shoshone River, tentatively correlated with his Fort Union (?) formation. He also concluded that the overthrust was older than the "early basic breccias."

The short time available to the writer in this region in 1919 only permitted the following conclusions:

1. The beds exposed along the north fork of Shoshone River under the "early basic breccias" (13), and locally under remnants of the overthrust block resemble lithologically those 1,000 to 1,500 feet above the base of the Fort Union formation in the Bighorn Basin and lack the arkoses which are rather characteristic of the Bighorn Basin Wasatch. On the other hand they yield collections of leaves, among which F. H. Knowlton has recognized "Aralia notata Lesq." which though considered to be a Fort Union species, has not yet been recognized in the Bighorn Basin Fort Union, but is present in most of the collections from the "early acid breccias" in Yellowstone Park and the tuffs north of Owl Creek. The beds yield numerous bone fragments, largely turtle skutes, not yet recognized in the Bighorn Basin Fort Union, but common in the Bighorn Basin Wasatch. Although existing evidence is conflicting, the writer is inclined to consider that the beds are to be correlated with the border Wasatch.

2. The overthrust is older than the "early basic breccias" because the breccias locally lie in channels cut 200 to 300 feet below the overthrust surface.

3. The period of erosion that followed the overthrust and preceded the deposition of the "early basic breccias" was sufficiently long to destroy most of the beds that made up the thrust block, for the thickest remnant, that which makes up the summit of

Sheep Mountain, is only 1,000 feet thick and there are large areas over which the block is completely removed and "early basic breccias" rest on Wasatch beds (?).

TERTIARY DEFORMATION AND SEDIMENTATION IN THE BIGHORN BASIN

The table opposite p. 556 is presented at this time in the hope that it may aid in a better understanding of the relation of the Heart Mountain overthrust to the other deformations of the Bighorn Basin. It is not considered necessary to present in this paper any more of the evidence on which the conclusions are based.

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Geologic Age		Absaroka-Owl Creek Mountain Front		Border B
		Deposition or Erosion	Deformation	Deposition or Erosion
Miocene	Upper	Early basic breccias (widespread)		Basic tuff (?) (local)
	Lower	Erosion		Erosion (?)
Oligocene		Erosion		Erosion
Eocene	Upper	Erosion	Normal faults (local)	Erosion
		(Unconformity (?))	Heart Mountain overthrust	(Unconformity (?))
	Middle	"Early acid breccia" (local)		Andesitic tuffs (local)
		(Conformity) Border Wasatch (local)		(Conformity) Border Wasatch (local)
	Lower	Erosion		Erosion
		(Unconformity)		(Unconformity)
Basal Eocene ("Paleocene")		Fort Union (?)	Extensive normal faults Large folds Widespread uplift Sinking (?)	Fort Union
		(Local unconformity)		(Local unconformity)
Tertiary (?)[1]		Lance formation (?)	Local warping Sinking (?)	Lance formation

[1] The Lance formation is here placed in the Tertiary (?) to conform with the usage formability with the underlying cretaceous beds.

RY DEFORMATION AND SEDIMENTATION IN BIGHORN BASIN

Bighorn Basin			
Border Belt		Central Part	
osition or Erosion	Deformation	Deposition or Erosion	Deformation
sic tuff (?) (local)		(?)	
osion (?)		Erosion (?)	
osion		Erosion (?)	
osion	Normal faults (local)	Erosion (?)	
nconformity (?))	Heart Mountain overthrust	(?)	Heart Mountain overthrust
desitic tuffs (local)		Andesitic tuffs (?) (local)	
nformity)		(?)	
Border Watch (local)		Bighorn Basin Wasatch: Tatman Mtn. beds; Lost Cabin beds; Lysite beds; Gray Bull beds; Sand Coulee beds — Subdivisions of Sinclair and Granger	Local depression
osion			
nconformity)	Local normal faults Small folds Local uplift	(Unconformity (?))	Depression
rt Union	Widespread sinking	Clark Fork beds of Sinclair and Granger Fort Union	Widespread sinking
cal unconformity)		(?)	
	Local warping		(?)
nce formation	Sinking	Lance formation	Sinking

rm with the usage of the U.S. Geological Survey, although the local evidence indicates con-

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SUMMARIES OF PRE-CAMBRIAN LITERATURE OF NORTH AMERICA

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INTRODUCTORY

In 1915, summaries of pre-Cambrian literature from 1909 to 1915 were published in the *Journal of Geology*. The summaries published herewith bring this review nearly down to date. For 1919, attention has been given only to those publications which are likely to contain important papers on the pre-Cambrian. Emphasis in these summaries is placed on stratigraphic facts and problems.

I. LAKE SUPERIOR REGION AND ISOLATED PRE-CAMBRIAN AREAS OF THE MISSISSIPPI VALLEY

In the Lake Superior region notable contributions to the stratigraphy of the pre-Cambrian have been made by Wolff, Grout and Broderick, Hotchkiss, and Allen and Barrett. The tendency has been to subdivide the iron formations of the leading districts into several units and to connect the occurrence of major ore deposits with certain of these units. In the main productive portion of the Mesabi district, Wolff from his extended experience in drilling and mining has recognized four divisions of the Biwabik iron formation. Grout and Broderick have recognized similar units in the eastern, less-productive portion of the formation. Hotchkiss has found an unconformity in the Ironwood iron formation of the Gogebic district and has recognized two units in the upper division and three in the lower. He has also found an unconformity between the iron formation and the overlying Tyler slates. The recognition of these new unconformities, Hotchkiss believes, does not call for a revision of correlation. Allen has discovered an unconformity cutting the Upper Huronian

formations of Van Hise and Leith in the eastern part of the Gogebic district. Between the Keweenawan and this unconformity, Allen finds a series of clastic sediments which are neither Keweenawan nor Upper Huronian. Allen decides that the Upper Huronian of Van Hise and Leith is to be correlated with the Middle Huronian of the Marquette district. On much less convincing evidence than in the Gogebic district he also concludes that a Middle Huronian is found in the Menominee district. Following these studies, a revised correlation of the Lake Superior region is offered by Allen in which all the important iron formations of the region are designated as Middle Huronian.

Allen has made important studies of the region between the Penokee and Iron River districts, but owing to the drift cover of the area he has not obtained the facts for a satisfactory correlation of the Iron River with the Penokee and Marquette districts. He has also studied the Gwinn district and the eastern extension of the Menominee district.

R. C. Allen[1] believes that the pre-Cambrian rocks of the Gwinn district located about sixteen miles south of Marquette, Michigan, comprise two unconformable series which he correlates with the Upper and Middle Huronian respectively. The succession according to Allen is shown on page 560.

The graywacke and conglomerate near the middle of the sedimentary succession constitutes the evidence on which Allen bases his conclusion for unconformity in the Huronian system. The conglomerate contains fragments which resemble the underlying sediments including iron ore. The two unconformable series appear to be structurally concordant however.

His correlation of the lower series with the Middle Huronian is based on the fact that the Lower Huronian is not known to contain iron formation of the type in the Gwinn district.

Allen and Barrett[2] believe that the acid mica schists of Wolf Lake are the metamorphosed equivalent of the Paint slates of

[1] R. C. Allen, "Correlation and Structure of the Pre-Cambrian Rocks of the Gwinn Iron Bearing District of Michigan," *Jour. Geol.*, Vol. XXII, No. 6 (1914); also in *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 161–64.

[2] R. C. Allen and L. P. Barrett, "The Paint Slate and the Wolf Lake Granite, Gneiss and Schist," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 131–39.

the Iron River and Crystal Falls districts. The granite intrusive into them, they believe, is of the same age as their Presque Isle granite of the Gogebic district. Wolf lake is situated between the Iron River and Gogebic districts.

Quaternary—Pleistocene glacial deposits
Ordovician and Cambrian—limestone and sandstone
Algonkian—Keweenawan, probably represented by certain basic dikes which cut all formations

Upper Huronian Princeton series	Slate, ferruginous slate, chert and quartzite, quartzite	Equivalent of Michigamme slate
	Conglomerate graywacke	Equivalent of Goodrich quartzite of Marquette district
Unconformity		
Middle Huronian Gwinn series	Gray slate Black slate Iron formation Gray slate Black slate	Equivalent of Negaunee iron formation and Siamo slate
	Arkose Conglomerate	Equivalent of Ajibik slate

Unconformity
Archean system
Laurentian—Granite and greenstone, mainly granite
Keewatin

Allen and Barrett[1] find that the pre-Cambrian rocks at the Little Lake Hills about seven miles east of the Gwinn district of Michigan consist from the base upward of conglomerate, arkose, and quartzite separated by an unconformity from a conglomerate quartz slate and quartzite respectively. The strata appear to be concordant, but the conglomerate near the middle of the column is clearly basal. The lower series is correlated with the Middle Huronian Gwinn series of the Gwinn district; the upper series with the Upper Huronian–Princeton series of the aforementioned district. The absence of iron formation in the Little Lake Hills, Middle Huronian is thought by the writers to indicate the depth of erosion of the Gwinn series before the Princeton series were laid down.

[1] R. C. Allen and L. P. Barrett, "Evidence of the Middle-Upper Huronian Unconformity in the Quartzite Hills at Little Lake, Michigan," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 153–59.

Allen[1] finds a series of magnetic belts in a region covered by Paleozoic rocks and glacial drift extending east of Waucedah on the Menominee range to Escanaba, a distance of about twenty-eight miles. From Waucedah, the buried eastward extensions of two productive iron formations have been traced for six miles by magnetic survey. The detached magnetic belts east of this limit may or may not be equivalent to the iron ranges at Waucedah. They undoubtedly represent belts of folded sedimentary rocks which may include iron formation.

Allen and Barrett[2] describe the Conover district of northern Michigan, about forty-five miles southeast of the Gogebic range, as a drift-covered area showing several magnetic belts. Drilling has shown that the underlying rocks are slates intruded by granites. The authors believe that the slates are the equivalent of the iron-bearing slates of the Iron River district.

Allen and Barrett[3] state that the existence of the Manitowish range is indicated by a series of strong, parallel linear magnetic belts about twenty-five miles southeast and parallel to the Gogebic range. Drilling has shown that the underlying drift-covered rocks are mica schists intruded by granites.

Allen and Barrett[4] report that the Vieux Desert district of Wisconsin and Michigan lying about forty miles southeast of the Gogebic range is a deeply drift-covered area showing several faint magnetic belts. As shown by drilling, the underlying rocks are acid gneisses and schists.

Allen and Barrett[5] correlate the strongly magnetic iron formation of the Marenisco range with the Ironwood formation of the

[1] R. C. Allen, "Relative to an Extension of the Menominee Iron Range Eastward from Waucedah to Escanaba, Michigan," *Econ. Geol.*, Vol. IX, No. 3 (1914), pp. 236–38, 1 map; also in *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15.

[2] R. C. Allen and L. P. Barrett, "Geology of the Conover District," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 123–29.

[3] R. C. Allen and L. P. Barrett, "Geology of the Manitowish Range," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 111–17.

[4] R. C. Allen and L. P. Barrett, "Geology of the Vieux Desert District," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 119–21.

[5] R. C. Allen and L. P. Barrett, "Geology of the Marenisco Range," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 65–86.

Gogebic district. Both are classified by them as Middle Huronian. The succession in the Marenisco range, they state, is as follows:

Keweenawan		Diabase
	Igneous contact	
Huronian	Middle Huronian (Animikie)	Intrusive granite Intrusive greenstone Slate Extrusive lavas Iron formation Quartzite and graywacke
	Unconformity	
Archean	Northern Area—granite and greenstone Southern Area—mica schist, green schist, and amphibolite (may be Huronian)	

The Marenisco range lies three to twelve miles south of and is parallel to the Gogebic range.

Allen and Barrett[1] describe the Turtle iron range about eighteen miles southeast of and parallel to the Gogebic range of northern Wisconsin and Michigan. The succession of the range as stated by the authors is as follows:

ALGONKIAN:		
Keweenawan	Intrusive diabase Granite and greenstone	
Huronian	Middle Huronian (Animikie)	Granite Effusive Agglomeratic and ellipsoidal Greenstone Black slate and graphitic schist Iron formation Quartzite and mica schist
	Unconformity?	
	Lower Huronian	Mica schist (may be Middle Huronian) Dolomite and dolomitic quartzite Quartzite
	Unconformity	
ARCHEAN:		
Keewatin	Mica schist and green schist	

[1] R. C. Allen and L. P. Barrett, "Geology of the Turtle Range," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 86–109.

Allen and Barrett[1] find that a group of dominantly clastic sediments overlie with marked unconformity the Upper Huronian of Van Hise and Leith in the Gogebic district. They also find that a granite intrudes the Upper Huronian. Their threefold division of the rocks between the Keweenawan and the Archean of the Gogebic, they claim, identifies this succession with the three Huronian divisions of the Marquette district. They designate as Middle Huronian, the Upper Huronian of Van Hise and Leith in the Gogebic district and extend this change to the correlation by these authors to every other district of the Lake Superior region, outside of the Marquette district. The revised correlation table which Allen and Barrett offer places every important Lake Superior iron formation excepting that of the Vermilion district in the Middle Huronian.

In 1919, Allen[2] extended to the Menominee district the threefold classification of the Huronian which he had found applicable to the Gogebic district of northern Michigan. His revised correlation of the Huronian of the Menominee district is shown on page 564.

In previous correlations of the Menominee, notably that of Bayley in Monograph 46 of the U.S. Geological Survey, the Middle and Upper Huronian of Allen were regarded as a conformable succession designated Upper Huronian. Van Hise and Leith, in 1911, recognized a Middle Huronian quartzite, but later Leith is said to have given up this revision. Allen bases his separation of the Upper Huronian of Bayley on the fact that some drill holes have shown what is interpreted as a basal conglomerate between the Hanbury slate and the Curry iron formation. Many drill holes do not show this conglomerate. He also appeals to the fact that the Randville dolomite in different places is covered by various formations ranging from the Traders iron formation to the Hanbury slates. Bayley had accepted one of the alternative explanations for this fact, viz., that the formations overlying the Randville were all conformably deposited on a very uneven surface of the

[1] R. C. Allen and L. P. Barrett, "Contributions to Pre-Cambrian Geology," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 13–164, 12 pls., 11 figs., maps.

[2] R. C. Allen, "Correlation of Formations of Huronian Group in Michigan," *Am. Inst. Min. and Met. Eng.* (1919), No. 153, pp. 2579–94.

Randville. Allen emphasizes this relation of the Hanbury slate as evidence of unconformity with the Curry iron-formation group. No proof of angular discordance between the Hanbury slates and the Curry iron formation seems to have been found by Allen. His recognition of the Loretto slate is based on the fact that on a certain

Period	Epoch	Stage	Formation
Epi-Huronian	Revolution	Emergent interval	Granite
Huronian	Upper Huronian	Quinnesec	Eruptive contact, basic extrusives, sills and dikes
		Hanbury	Great slate series with beds of conglomerate, quartzite, graywacke, ferruginous chert, and impure limestone. Thickness?
	Emergent	interval	
	Middle Huronian	Loretto	Slate 400 feet
		Curry	Iron formation 100 to 200 feet
		Brier	Ferruginous, siliceous banded slate 300 to 400 feet
		Traders	Conglomerate, quartzite, and iron formation 150 feet
	Emergent	interval	
	Lower Huronian	Randville	Dolomite, cherty dolomite, and talcose facies 1,000 to 1,500 feet. Conglomerate, arkose, graywacke, and quartzite 1,200 feet
	Great Archeozoic interval		

forty-acre lot, a few drill holes passed through what he assumes to be the basal Hanbury conglomerate and then through a slate before striking the Curry iron formation. It appears that Allen's revision is based solely on a very local occurrence of a fragmental rock above the Curry iron formation.

Broderick[1] presents a detailed classification of the beds of the Biwabik iron formation in the eastern part of the Mesabi range. He retains Wolff's general classification into Upper slaty

[1] T. M. Broderick, "Detail Stratigraphy of the Biwabik Iron Bearing Formation, East Mesabi District, Minnesota," *Econ. Geol.*, Vol. XIV (1919), pp. 441–51.

beds, Upper cherty beds, Lower slaty beds, and Lower cherty beds.

Broderick[1] interprets certain negative magnetic lines of the Duluth gabbro as due to a certain angle of inclination of the magnetic formations with the horizontal.

According to Cayeux[2] traces of crinoids are found in the iron formations of the Gogebic, Mesabi and Menominee ranges. They consist of circular, quadrilateral, and hemispherical bodies larger than the oölites and of polygonal cells whose walls are composed of iron. The cells occur with and without alignment.

Grout[3] finds that siliceous pegmatites formed on all sides of the basic Duluth gabbro, but that distinct dikes occur only outside the contact. He infers that the two magmas separated in the liquid state.

Grout[4] presents interesting petrographic descriptions of the Biwabik iron formation of the eastern part of the Mesabi district. He concludes that originally the iron formation was a shallow water deposit formed mainly by organic processes.

Grout[5] proposes the name lopolith for intrusions like the Duluth gabbro whose floors and roof sag downward toward the middle. Evidence is introduced for concluding that the main mass of this intrusion was along a plane of unconformity. Suggestions are made that the method of intrusion of the lopolith is different from that of a laccolith.

Grout believes, as indicated by his diagrams, that the dip of the pre-Cambrian beds around the western rim of Lake Superior is due to settling rather than compression. It would be interesting to find out whether the nature of the fracture and flow cleavage structures in these formations checks with this view.

[1] T. M. Broderick, "Some Features of Magnetic Surveys of the Magnetic Deposits of the Duluth Gabbro," *Econ. Geol.*, Vol. XIII (1918), pp. 35–49.

[2] L. Cayeux, "Existence de restes organique dans le roche ferruginenses associées aux minérais de fer huroniens des Etats-Unis," *Acad. Sci. Paris Compt. rend.*, Vol. 153, pp. 910–12.

[3] F. F. Grout, "The Pegmatites of the Duluth Gabbro," *Econ. Geol.*, Vol. XIII (1918), pp. 185–97.

[4] F. F. Grout, "The Nature and Origin of the Biwabik Iron Bearing Formation of the Mesabi Range, Minnesota," *Econ. Geol.*, Vol. XIV, (1919), pp. 452–64.

[5] F. F. Grout, "Lopolith, an Igneous Form Exemplified by the Duluth Gabbro," *Am. Jour. of Science*, Vol. CXCVI (1918), pp. 516–22.

Grout[1] states that the Duluth gabbro lopolith shows differentiation into the gabbro and granite families and discusses the problem of the processes of differentiation.

Hore[2] presents descriptions of the most important copper lodes of Upper Michigan, and reviews the literature of the region. He concludes that the ores are replacement deposits formed by chloride solutions liberated with the formation of the traps in which they occur or with which they are associated; that they have not been modified except in very minor ways since they were formed; but that the rocks in which they are formed were farther tilted since the ores were formed.

Hotchkiss, Bean, and Wheelwright[3] map a part of the pre-Cambrian area of Ashland, Bayfield, Washburn, Sawyer, Price, Oneida, Barron, Rusk, and Chippewa counties. The chief aim of the work is to show the distribution of iron-bearing formations. Since the area is nearly all drift-covered, magnetic surveys furnish most of the facts. The pre-Cambrian sediments are classed as Barron quartzite and undivided Huronian. Keweenawan traps and granites and gneisses probably of various ages are found in the area. The report has notable chapters on field methods used in work of this type and on the nature and interpretation of magnetic data.

Hotchkiss[4] has made an important contribution to the study of the stratigraphy and structure of the Gogebic iron district of northern Wisconsin and Michigan. The influence of stratigraphy and structure on the formation of the ores is also discussed by him. Many new facts and relationships are presented. Although he recognizes several new unconformities in the succession, he does not believe that the facts now known warrant any fundamental

[1] F. F. Grout, "A Type of Igneous Differentiation," *Jour. Geol.*, Vol. XXVI (1918), pp. 626–58.

[2] R. E. Hore, "Michigan Copper Deposits," *Mich. Geol. Surv. Pub. 19* (1915), pp. 19–161, 18 pls., 16 figs.

[3] W. O. Hotchkiss, "Mineral Land Classification Showing Indications of Iron Formations," *Wis. Geol. Surv. Bull. No. 44* (1915), 378 pp., 8 pls., 39 figs. (incl. maps).

[4] W. O. Hotchkiss, "Geology of the Gogebic Range and Its Relation to Mining Developments," *Eng. and Min. Jour.*, Vol. CVIII (1919), pp. 443–52, 501–7, 537–41, 577–85.

revision of the classification by Van Hise and Leith. The essentials of the stratigraphic classification by Hotchkiss follow:

Keweenawan sandstones and conglomerates overlain by basic flows

Unconformity

Tyler graywacke slate 0–2 miles thick	Graywacke slates Iron carbonate slates Pabst member-cherty and fragmental slate beds

Unconformity

Upper Ironwood formation	Anvil wavy-bedded ferruginous chert member Pence even-bedded ferruginous slate member

Slight unconformity

Lower Ironwood formation	Norrie wavy-bedded ferruginous chert member Yale member—interbedded ferruginous cherts and ferruginous slates Plymouth member—wavy-bedded ferruginous chert (most mines located on this member)

Palms quartzite 400 feet to 800 feet

Unconformity

Bad River cherty dolomite with quartzite below in eastern part of district

Unconformity

Granite and green schist both of igneous origin

The unconformities within the Ironwood formation and between the Tyler slate and the Ironwood formation have not been described before. Their existence is inferred from basal conglomerates and evidences of erosion of the members underlying the unconformity.

Lane[1] finds that the strata on the east side of the Copper range were uplifted and the eastern sandstone deposited on them. The Trap range subsequently overrode the sandstones in places several hundred feet.

Leonard[2] states that pre-Cambrian granite struck in wells of the Red River valley is the only known pre-Cambrian rock of North Dakota.

[1] A. C. Lane, "Abstract," *Bull. Geol. Soc. of America*, Vol. XXIV (1913), p. 718.

[2] A. G. Leonard, "The Geology of North Dakota," *Jour. Geol.*, Vol. XXXVII (1919), pp. 1–27.

Leith[1] suggests that the unconformity at the base of the Cambrian was developed by a process of cut and fill, and that the common occurrence of late pre-Cambrian terrestrial sediments is more than a coincidence, but is related to the development of the basal Paleozoic unconformity.

Nebel[2] presents a petrographic study of certain basal portions of the Duluth gabbro and its contact effects.

Powers[3] reports that drilling in the east-central portion of Kansas has shown the existence of pre-Cambrian granite of considerable relief occurring along a north-south line.

Wolff[4] reports that the average thickness of the Mesabi iron formation is six hundred and twenty feet, and that it consists of four divisions which from the top down are as follows: Upper slaty horizon, Upper cherty horizon, Lower slaty horizon, and Lower cherty horizon. The ores occur chiefly in the two cherty horizons and in the Lower slates. Marked differences exist between the ores of the various horizons.

[1] C. K. Leith, "Relations of the Plane of Unconformity at the Base of the Cambrian to Terrestrial Deposition in Late Pre-Cambrian Time," *Congrès Géologique International*, XII. Session Canada, pp. 333–37.

[2] M. L. Nebel, "The Basal Phases of the Duluth Gabbro Near Gabamichigami Lake, Minnesota, and Its Contact Effects," *Econ. Geol.*, Vol. XIV (1919), pp. 367–402.

[3] Sidney Powers, "Granite in Kansas," *Am. Jour. of Science* (4th ser.), Vol. XLIV (1917), pp. 146–50, 1 fig.

[4] J. F. Wolff, "Recent Geologic Developments on the Mesabi Range, Minnesota," *Am. Inst. Min. Eng. Bull. No. 118* (1916), pp. 1763–87, 14 figs.

[*To be continued*]